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RRTAC 88-9

Computer Analysis Of The Factors Influencing Groundwater Flow And Mass Transport In A System Disturbed By Strip Mining

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LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

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Report No. RRTAC 88-9

COMPUTER ANALYSIS OF THE FACTORS INFLUENCING GROUNDWATER FLOW AND MASS TRANSPORT IN A SYSTEM DISTURBED BY STRIP MINING

by

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Prepared under Contract

to

Alberta Research Council

for

The Plains Coal Reclamation Research Program

of the

ALBERTA LAND CONSERVATION AND RECLAMATION COUNCIL
(Reclamation Research Technical Advisory Committee)

1988

DISCLAIMER

The recommendations and conclusions in this report are those of the author and not of the Alberta Government or its representatives.

This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

ALBERTA'S RECLAMATION RESEARCH PROGRAM

Regulating surface disturbances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a Chairman from Alberta Environment and two deputy chairmen from Alberta Forestry, Lands and Wildlife. The Council oversees a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program is provided by Alberta's Heritage Savings Trust Fund Land Reclamation Program.

To assist with development and administration of the research program, the Council appointed the interdepartmental Reclamation Research Technical Advisory Committee (RRTAC). The Committee consists of eight members representing the Alberta Departments of Agriculture, Forestry, Lands and Wildlife, Environment, and the Alberta Research Council. The Committee updates research priorities, reviews solicited and unsolicited research proposals, organizes workshops, and otherwise acts as the coordinating body for reclamation research in Alberta.

Additional information on the Reclamation Research Program may be obtained by contacting:

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RECLAMATION RESEARCH REPORTS

** 1. RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp.

DESCRIPTION: This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

** 2. RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi, and H.F. Regier. 160 pp.

DESCRIPTION: Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

N/A 3. RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker, and D.F. Polster. 2 vols, 541 pp.

DESCRIPTION: Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

N/A 4. RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp.

DESCRIPTION: This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

N/A 5. RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch, and G. Lutwick. 253 pp.

DESCRIPTION: Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

N/A 6. RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp.

DESCRIPTION: Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

N/A 7. RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology, and Groundwater. C.B. Powter and H.P. Sims. 97 pp.

DESCRIPTION: This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

N/A 8. RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp.

DESCRIPTION: Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

N/A 9. RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp.

DESCRIPTION: Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

N/A 10. RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz. 123 pp.

DESCRIPTION: Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

N/A 11. RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp.

DESCRIPTION: This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

*** 12. RRTAC 84-1: Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter, and J.A. Campbell. 2 vols, 1549 pp.

DESCRIPTION: Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

** 13. RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp.

DESCRIPTION: This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

* 14. RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 15. RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser, and J.C. Zak. 2 vols, 676 pp.

DESCRIPTION: This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.

** 16. RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz. 416 pp.

DESCRIPTION: Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

* 17. RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 18. RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp.

DESCRIPTION: The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.

** 19. RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp.

DESCRIPTION: Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

* 20. RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp.

DESCRIPTION: In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

** 21. RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp.

DESCRIPTION: This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

** 22. RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp.

DESCRIPTION: This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

* 23. RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp.

DESCRIPTION: The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta

* 24. RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp.

DESCRIPTION: This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

* 25. RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 26. RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp.

DESCRIPTION: This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

** 27. RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp.

DESCRIPTION: Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

** 28. RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp.

DESCRIPTION: This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

** 29. RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (compiler). 218 pp.

DESCRIPTION: Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

* 30. RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

* 31. RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp.

DESCRIPTION: The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

** 32. RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp.

DESCRIPTION: The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

* 33. RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp.

DESCRIPTION: The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

* 34. RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp.

DESCRIPTION: This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

** 35. RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Areas. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp.

DESCRIPTION: This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

** 36. RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps.

DESCRIPTION: The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

** 37. RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp.

DESCRIPTION: The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

** 38. RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp.

DESCRIPTION: This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

* 39. RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp.

DESCRIPTION: This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

** 40. RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix.

DESCRIPTION: The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

** 41. RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (compiler). 135 pp.

DESCRIPTION: Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

** 42. RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp.

DESCRIPTION: The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their uninoculated counterparts.

** 43. RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp.

DESCRIPTION: This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

** 44. RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.H. Danielson and S. Visser. 177 pp.

DESCRIPTION: The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

* 45. RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp.

DESCRIPTION: This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

* 46. RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp.

DESCRIPTION: Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

** 47. RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey, Alberta Forest Service. 4 Sections, various pagings.

DESCRIPTION: Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

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N/A Not available for purchase but available for review at the Alberta Environment Library, 14th Floor, 9820 - 106 Street, Edmonton, Alberta T5K 2J6

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PREFACE

This is one of a series of reports that present the findings of the Plains Hydrology and Reclamation Project (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of reclamation of surface coal mines in the plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Land Conservation and Reclamation Council and is supported by the Heritage Savings Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that, in the future, mine sites that are not totally analogous to those that have been studied can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP was directed toward the following two major objectives and eight subobjectives.

Objective A

To evaluate the potential for reclamation of lands to be surface mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five subobjectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt build-up.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of materials to mitigate deleterious impacts on chemical quality of groundwater.
3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining

landscapes and the significance of changes in capability as a result of mining.

5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three subobjectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at the Highvale Mine south of Lake Wabamun. Significant progress had been made on all projects objectives by the end of the first phase of the study in March 1984. This present series of reports summarizes the state of our knowledge at the end of this phase of the study. Work is now continuing on the Phase II objectives to gain an even greater understanding of the complex physical and chemical processes in reclaimed landscapes.

Work presented in this report, which relates to a number of the project subobjectives, demonstrates how a groundwater flow model can be used to study a variety of mining-related problems. One major problem related to the development and reclamation of coal strip mines is the decline in water levels in areas around the mine as a consequence of dewatering (Subobjectives A1, B1, and B2). A second major problem relates to the high water tables that can develop in spoil once resaturation is complete (Subobjectives A1 and B1). In semi-arid regions this condition can lead to soil salinization. Generally, emphasis in the study of these problems has been placed on detailed field and laboratory studies of existing or proposed mines. Such studies have been extremely important in establishing base-line data on the hydrogeological setting in relation to mine development, and in defining impacts related to mining. However, field-oriented studies are limited because of their concentration in the relatively short periods of time, perhaps several years, and on a relatively local area in and around the mine site. Thus, it is difficult to predict long-term or regional effects from field studies alone.

This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional-scale where the area of the mine is relatively small in relation to the size of the flow domain. Moving to what we term a "mine-scale", where the mine becomes a significant component of the total setting, the objective is to look at the spoil restaturation process with emphasis on the controls exerted by hydraulic conductivity and recharge rates.

The smallest scale that is considered is the individual hills that are formed in spoil during reclamation. The objective of the sensitivity analyses carried out at this scale is to show how hydraulic conductivity of the spoil, recharge rates and the presence of drains together with hill morphology control the steady state configuration of the water table. Not only will these analyses provide a better understanding of the processes involved, but they should also serve as a guide to reclamation strategies.

The modelling approach presented here represents a major advance on existing work in several different ways. First, there is the unique treatment of groundwater flow around mines as a free surface problem using a finite element approach. Second, the mining process is represented in several different simulations much more realistically than was the case in other studies. Finally, unlike other work, we have tended to emphasize the behaviour of flow systems and the patterns of spoil restauration once mining has been completed.

ABSTRACT

This study demonstrates how groundwater flow models can be used to study the long-term response of groundwater flow patterns in and around strip mines, particularly once mining and reclamation are complete. The two-dimensional, finite element model developed during this study extends previous work with its ability to simulate the actual steps in mining and reclamation, and its treatment of groundwater flow using a transient, free surface approach. Simulation trials presented here are carried out on three significantly different scales. In the regional-scale simulations, the entire mine is a relatively small component of an extensive hydrogeological system. Here, changes in groundwater levels are controlled by: (1) the presence of local discharge areas or sources of recharge; (2) the character of the post-mining landscape; (3) changes in the rate of recharge through the spoil; and (4) changes in the hydraulic conductivity of the spoil relative to the undisturbed geological materials. The timing of water level changes depends upon how efficiently water is able to move to the low in hydraulic potential caused by mining and upon the storativity of the spoil. In the mine-scale simulations, the mine occupies a major portion of the system. These simulations show that spoil resaturation depends on the magnitude and distribution of recharge and the hydraulic conductivity of spoil and geological units. During the early phase of spoil resaturation, high gradients along the water table can develop due to, first a lack of bottom drainage through units below the mine or, second spoil with a low hydraulic conductivity. Conversely when conditions opposite to these develop, the gradients along the water table are relatively low. The timing of these water level changes depends upon recharge rates and the storativity of the spoil. At the smallest scale, individual hills comprised of spoil are the element of interest. Steady state water levels remain dependent upon recharge rates and hydraulic conductivity but are modified by hill size. A high water table is favoured by low hydraulic conductivities, high recharge rates, or hills with a wide base. While the addition of widely spaced surface drains are generally ineffective in controlling water levels, discrete open drains which are closely spaced within the spoil appear much more useful. Generally, the effect of a drain is independent of hill size.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The strip mining of large reserves of coal from the western plains region of Canada and the United States has raised concerns about the potential impact of mining on the environment. Indeed, there are a variety of groundwater problems related to the development and reclamation of coal strip mines. One major problem is the decline in water levels in areas around the mine as a consequence of dewatering (Kipp et al. 1979; Helgesen and Razem 1980; Lindorff 1980; Rehm et al. 1980; Hardaway 1981; Hickcox 1982a, b). A second major problem relates to the high water tables that can develop in spoil once resaturation is complete. In semi-arid regions, this condition can lead to soil salinization. To date emphasis in the study of these problems has been placed on detailed field and laboratory studies of existing or proposed mines. Large integrated field studies have been completed or are underway in Montana (Van Voast 1974; Rahn 1975; Van Voast and Hedges 1975; Van Voast et al. 1975, 1976, 1977, 1978; Dollhopf et al. 1979; Woessner et al. 1979), in North Dakota (Moran and Cherry 1977, 1978, 1981; Groenewold 1978; Moran et al. 1978, 1979; Palmer and Cherry 1979; Groenewold et al. 1980) in Wyoming (Rahn 1975; Rechard 1975), and in Alberta (Trudell and Moran 1982; Moran et al. 1983). Such studies have been extremely important in establishing base-line data on the hydrogeological setting in relation to mine development, and in defining impacts related to mining.

Field-oriented studies are often limited to relatively short periods of time, perhaps several years, and to a relatively local area in and around the mine site. Thus, it is difficult to predict long-term or regional effects from field studies.

Work presented in this report is designed to demonstrate how a groundwater flow model can be used to study a variety of mining-related problems. At the regional-scale where the area of the mine is relatively small in relation to the size of the flow domain, we will illustrate the role of various hydrogeological parameters that influence the magnitude, timing and extent of water level changes during and following mining. Moving to what we term a "mine-scale", where the mine becomes a significant component of the total setting the objective is to look at the spoil resaturation process with emphasis on the controls exterted by hydraulic conductivity and recharge rates.

The smallest scale that is considered comprises the individual hills that are formed in spoil during reclamation. The objective of the sensitivity analyses carried out at this scale is to show how hydraulic conductivity of the spoil, recharge rates and the presence of drains together with hill morphology control the steady state configuration of the water table. Not only will these analyses provide a better understanding of the processes involved but they should also serve as a guide to reclamation strategies.

The modelling approach presented here represents a major advance on existing work in several different ways. First, there is the unique treatment of groundwater flow around mines as a free surface problem using a finite element approach. Second, the mining process is represented in several different simulations much more realistically than was the case in other studies. Finally unlike other work, we have tended to emphasize the behavior of flow systems and the patterns of spoil resaturation once mining has been completed.

There have been a variety of quantitative studies to examine groundwater conditions in relation to mining. Analytical techniques for solving equations of groundwater flow have been applied to the evaluation of idealized cases of flow around a mine cut (Sternberg and Agnew 1968; Van Voast 1974; McWhorter 1981; Moran and Cherry 1981). While the main advantage of the analytical approaches is their relative ease of application, more complex hydrogeological conditions usually require more powerful numerical techniques.

Work by McIntosh (1979), Helgesen and Razem (1980), Bair and Parizek (1981), and Koch and McIntosh (1981) has demonstrated the application of numerical models to determine drawdown in the vicinity of actual mines. Wilson et al. (1979) have presented similar generic analyses showing how modelling can be used for the design and evaluation of systems to control groundwater inflow to a strip mine. Other numerical modelling studies (for example Hamilton and Wilson 1977; Wilson and Hamilton 1978; Prunty and Kirkham 1979, 1980; Rogowski and Weinrich 1979; and Prunty 1981) have been concerned with the factors that operate during mining to control groundwater flow systems and flow within the mine spoil. These studies were based on two-dimensional steady state models where the position of the water table is assumed known and hence fixed. No attempt has been made in previous studies to examine the long-term response of water levels following mining and the placement of spoil. In general, these studies have shown the value of modelling techniques in generating a longer term perspective on the behavior of a groundwater system, and in examining the role of various hydrogeological parameters in controlling groundwater flow in the vicinity of a strip mine.

1.1 MODELLING METHODOLOGY

Two numerical approaches are possible for modelling groundwater flow in relation to surface mining. The first of these involves simultaneously modelling flow both in the saturated and unsaturated parts of the groundwater system (Neuman 1973). Because this method can deal with the continuum of pressure heads that exists in and between the saturated and unsaturated zones, the position of the water table can be defined without considering it to be a boundary within the system. A significant disadvantage of this approach is that considerably more data are required to characterize the unsaturated zone than the saturated zone. In addition, data for the unsaturated zone are not routinely collected in most site specific studies.

The second approach, adopted for this study, concentrates only on the saturated part of the flow system. It is assumed that the effect of the unsaturated zone can be approximated simply by fluxes of water at the water table. For many problems, this simplification is justifiable (Neuman and Witherspoon 1971). Inflow to, or outflow from, the saturated zone causes the water table to rise or fall and the hydraulic head distribution to change. For transient flow problems, it becomes necessary to both relocate the water table and to solve for hydraulic head during each time step. Major computational difficulties arise because of the necessity of providing the capability of changing the shape of the flow domain with time. As an example of a free surface problem, consider the flow of groundwater along the two dimensional cross-section shown in Figure 1a. Recharge moving downward through spoil at this hypothetical mining site results in a continuous rise of the water table and increased quantities of groundwater flow to the discharge area at the left end of the section. Patterns of groundwater flow in the domain are defined by simulating both the hydraulic head distribution within the saturated domain (S) and the position of the water table or free surface (F) (Figure 1b).

Another feature of the flow system in Figure 1a that is commonly observed in free surface problems is a "seepage face". A seepage face is a zone of free groundwater outflow from a system where the hydraulic head at any point along the seepage face is equal to the elevation at that point. The seepage face in Figure 1b corresponds to the line segment a-b.

The problem of solving for the position of the free surface and the hydraulic head distribution was first addressed by Taylor and Brown (1967) and Finn (1967). An alternative procedure was proposed by Neuman and Witherspoon (1970). This latter work, originally developed for a case of steady flow, was subsequently

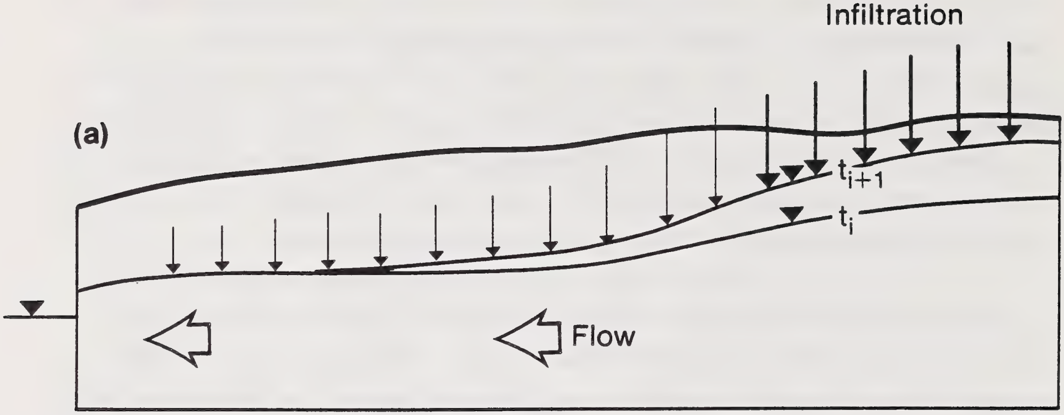


Fig. 1a. Schematic representation of groundwater flow in a two-dimensional cross section.

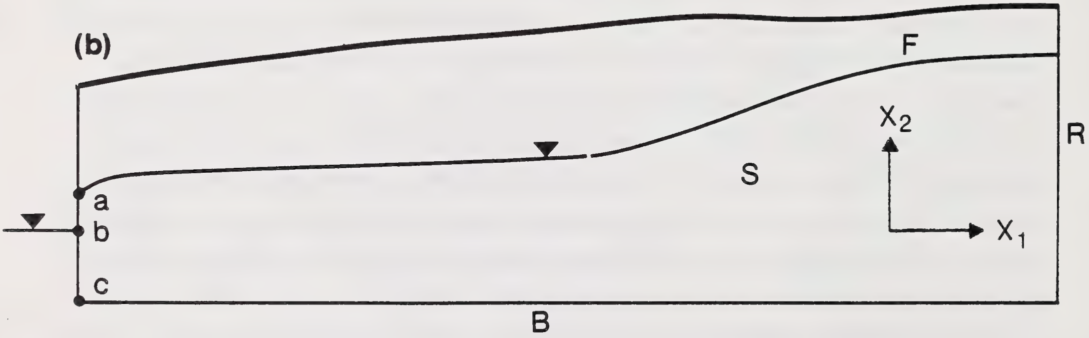


Fig. 1b. Various boundaries of the domain discussed in the text.

generalized to handle transient seepage problems with recharge across the free surface (Neuman and Witherspoon 1971). This basic theory and mathematical approach is followed in this study.

For problems like the one depicted in Figure 1a, Neuman and Witherspoon (1971) have developed a governing partial differential equation describing flow within the saturated domain, as described by equation (1), initial conditions, which are equations (2) and (3), and boundary conditions, given by equations (4) to (8).

$$\frac{\partial}{\partial x_i}\left[K_{ij}\frac{\partial h}{\partial x_i}\right] = S_S\frac{\partial h}{\partial t} \qquad \text{on S} \qquad \ldots\ldots(1)$$

$$h(x_i,0) = h_0(x_i) \qquad \ldots\ldots(2)$$

$$\delta(x_1,x_2,0) = \delta_0(x_1,x_2) \qquad \ldots\ldots(3)$$

$$h(x_i,t) = H(x_i,t) \qquad \text{on b-c} \qquad \ldots\ldots(4)$$

$$K_{ij}\frac{\partial h}{\partial x_j}n_i = -Q(x_i,t) \qquad \ldots\ldots(5)$$

$$\delta(x_1,x_2,t) = h(x_1,x_2,\delta,t) \qquad \text{on F} \qquad \ldots\ldots(6)$$

$$K_{ij}\frac{\partial h}{\partial x_i}n_i = \left[I - S_y\frac{\partial \delta}{\partial t}\right]n_2 \qquad \text{on F} \qquad \ldots\ldots(7)$$

$$h(x_i,t) = x_2 \qquad \text{on a-b} \qquad \ldots\ldots(8)$$

where: δ = elevation of free surface above a horizontal datum plane from which h is measured, (l)

h = hydraulic head, (l)

h_0 = initial hydraulic head, (l)

H = hydraulic head on constant head boundary, (l)

I = net vertical specific rate of infiltration at the free surface, (l / t)

K_{ij} = hydraulic conductivity tensor, (l / t)

n_i = unit outward normal vector, (l)

S_S = elastic specific storage, (l^{-1})

S_y = specific yield

Q = prescribed flux along a flux boundary, (l / t)

x_i = coordinate vector, i=1,2, (l)

t = time

l = length

As related to Figure 1b, equations (2) and (3) state that hydraulic head values and elevations of the free surface (F) must be assigned to appropriate nodes at the start of the simulation. Equation (4) indicates that fixed values of hydraulic head are assigned along b-c. No flow conditions are assumed along the bottom (B) and right side (R) of the domain and are described by (5). It is possible to modify conditions along these boundaries by fixing the hydraulic head at nodes or specifying prescribed fluxes. Equations (6) and (7) describe two different conditions that can occur along the free surface depending upon whether fluxes are present or not. Finally, (8) states that hydraulic head along the seepage face (a-b) is a function of elevation.

Following is a brief overview of the finite element technique and a description of the procedure for calculating the hydraulic head distribution and the position of the water table. A two-dimensional cross section, parallel to the direction of regional flow, is divided into discrete units of triangular finite elements. The incidences and nodal positions for each element are generated automatically in the computer code. In order to facilitate the automatic generation of meshes repeatedly throughout a simulation and to more closely conform to the geometry of the cross section, the grid blocks in the mesh are rectangular except along the upper boundary. One limitation related to the use of this rectangular mesh is that large contrasts in hydraulic conductivity between adjacent elements must be avoided in transient simulations. It is our experience that contrasts should be less than a factor of 50 in order to maintain numerical stability.

The set of grids shown schematically in Figure 2 illustrates how the grid is formed and adjusted through a series of time steps. Before the simulation commences, the grid system is formed, the initial value of hydraulic head is assigned and the initial position of the water table is defined (Figure 2a). At the beginning of any time step, the elevations of all nodes along the free surface are fixed and values of hydraulic head are calculated at all nodes within the flow domain and along the water table, which have not been designated as constant head nodes. In order for the

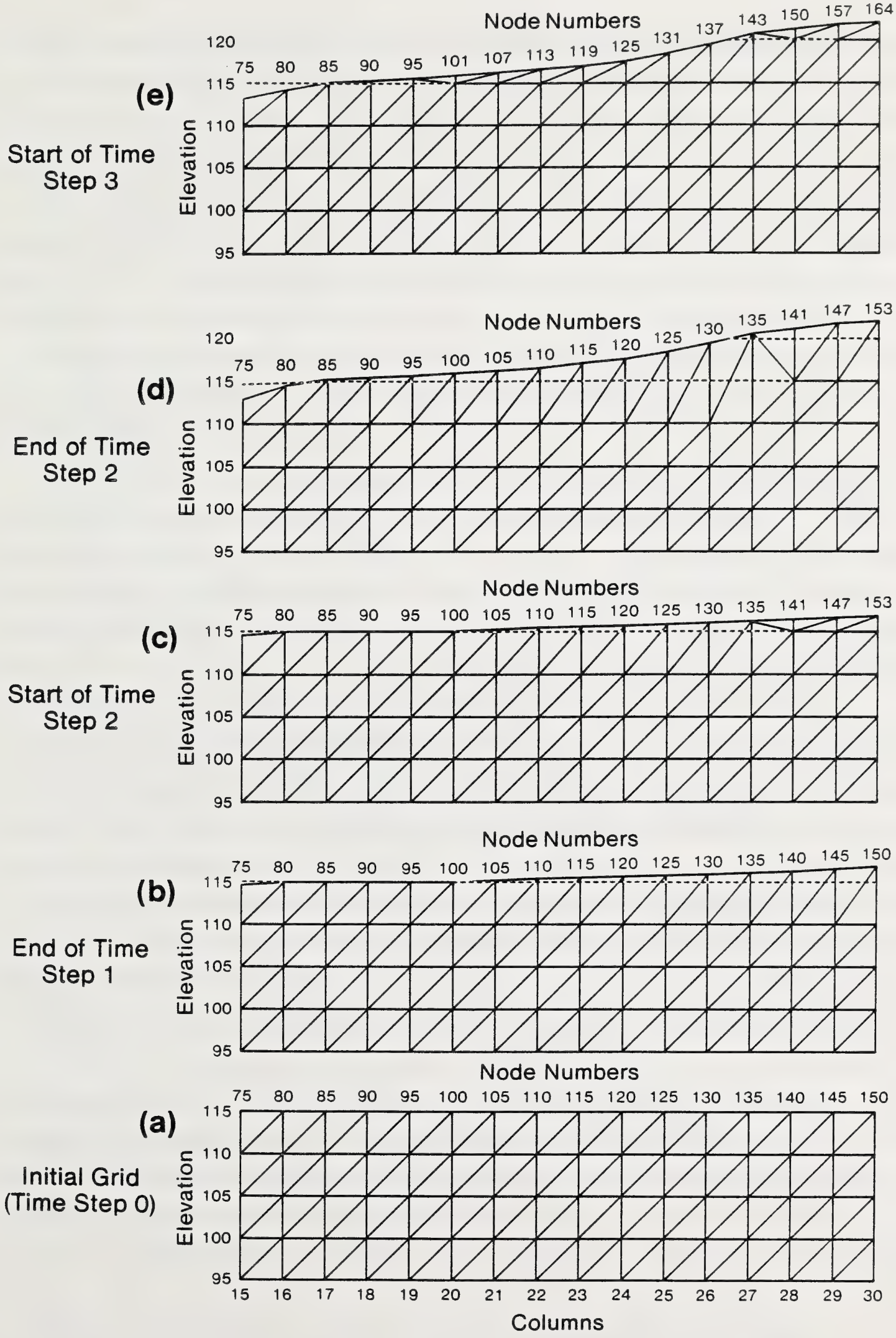


Fig. 2. A series of finite element meshes showing the manner in which the grid changes as a function of time with recharge along the top boundary.

position of the water table to be defined, the calculated head values along the free surface are compared to the elevation of these nodes to test whether the sum of the absolute value of their differences are less than a small tolerance value. If this condition is not met, the grid is adjusted by moving nodes at the free surface to an elevation equal to the calculated value of hydraulic head (Figure 2b). This entire procedure is repeated for successive iterations until the convergence criterion is met. Once the solution converges, the simulation moves to the next time step.

At the start of each succesive time step, the grid may be reconstructed by adding or removing nodes at the water table. In cases where the required adjustments to the free surface are only minor, nodes are simply moved causing the upper row of elements to stretch. However, once an element stretches more than 1/4 of the vertical node spacing, additional nodes and elements are added to the grid (Figure 2c). Conversely, if an element contracts by a given amount, nodes and elements could be removed. Using this procedure, it is possible to maintain a rectangular grid system except in the immediate vicinity of the water table. Maintaining a regular grid overcomes the problem of fitting elements to the geological units, which might develop if all the elements are allowed to stretch.

The model has been constructed with the capability to simulate the process of mining in an approximate way. We use this feature of the code at both the regional and mine scales. These simulations actually begin with a specified pre-mining hydraulic head distribution, proceed through a mining phase and end at some time following the cessation of mining during the so called post-mining phase. Even if only the post-mining response of the system is of concern, it is necessary to carry out the complete sequence of simulation steps. Initial values of hydraulic head can not usually be specified except before mining actually begins. The distribution of hydraulic head during the mining and post-mining phases can not be estimated well enough to establish initial conditions.

The numerical implementation of the mining process involves modifying the finite element grid near the water table to account for the presence of the open cut. Constant head nodes are defined at the base of the open cut with hydraulic head values equal to the elevation of the base of the cut. This condition implies that dewatering and draining of a cut maintains the water level at the elevation of the pit floor.

In addition, it is necessary to account for seepage faces that form at the pit wall. Nodes at the seepage face are defined as constant heads with values of hydraulic head equal to the elevation of the node. The elements at a seepage face are able to expand and contract according to the size of the seepage face. If gross changes occur in the size of the seepage face, nodes and elements are added following the procedure described above.

As mining continues, the adjacent cut is opened, the cut previously opened is filled with spoil, and heads along the pit floor and seepage faces are no longer fixed as constant. Reclamation, following the opening of the first cut, is simulated by placing fill from the cut being mined into the adjacent mined-out cut. Reclamation is assumed to proceed concurrently with the mining with the resultant levelling of the spoil piles. An option is provided in the computer code to either fill or leave open any cut.

Implicit in the two-dimensional approach is the assumption that the mine is infinite in the third dimension. Thus, the results of simulations apply directly to very long mines constructed across the regional flow system. The numerical approach has been verified by comparing solutions to the problem of the buildup of a groundwater mound due to infiltration. Our solution for the test problem compares well with that determined: 1) experimentally by Marino (1967); 2) analytically by Hantush (1963); and 3) numerically by Neuman and Witherspoon (1971).

All simulations in this report were carried out using an AMDAHL 5860 mainframe computer at the University of Alberta. A typical regional scale simulation requires 1200 to 1300 nodes. This would use approximately 850 000 bytes of core memory, of which approximately 630 000 bytes is use by the subroutines that solve the set of equations that calculate the hydraulic head distribution. The execution time increases with the complexity of the problem. However, for one regional simulation, required 38 seconds of CPU time and 15 time steps for the pre-mining regional steady state head distribution. The simulation of six mining and reclamation stages required approximately 20 seconds and the recovery of the post-mining flow system to steady state required 27 seconds for 13 time steps. The reader is referred to the companion volume to this report, which is a user's guide for the model, to obtain more information on the computer code, uses of the model and a more detailed discussion of memory and execution time requirements.

2. REGIONAL-SCALE SIMULATIONS

All of the simulations in this chapter focus on problems of a regional nature where the mine is a small element in a large regional system. This two-dimensional system, shown in Figure 3a is approximately 18 km long and ranges in thickness from 200 m to 260 m. Boundaries are designated as no-flow along the right end and bottom of the domain, and mixed no-flow and constant head along the left side. The ground surface rises relatively smoothly from a valley at the left end of the section. The general size of the domain and boundary conditions remains the same for all simulations. What does change is the hydraulic conductivity of the spoil and the geological units, the rates of recharge through spoil and the undisturbed area, and the topography of the ground surface.

These hydrogeological settings are hypothetical to the extent that basic model parameters are not derived from a particular field site. However, the choice of parameters has been guided by experience from a variety of field studies in the plains region of Canada and the United States.

Figure 3b illustrates the finite element grid that is used to simulate an initial pre-mining distribution of hydraulic head at steady state in the cross section depicted in Figure 3a. The grid consists of 61 columns and 25 rows, and contains approximately 1200 nodes and 2400 elements. The number of nodes and elements change as a function of the water table configuration during and following the period of mining. Figure 3c illustrates the depression of the water table and formation of seepage faces at a mine cut, and the modifications to the grid during mining. Simulation results for a simple example are shown to illustrate the entire sequence of mining steps required to generate results (Figure 4). The geology consists of a single unit with a hydraulic conductivity of 1×10^{-4} cm/s and a storativity of 5×10^{-4}. Recharge rates at the water table are 0.001 or 0.002 m/a. It is assumed that the spoil has the same hydraulic conductivity as the geological unit but a storativity of 5×10^{-3}. The recharge rate through the spoil is considered to be 0.0001 m/a. The mined area for this and all other cases represents a relatively small proportion of the total area along the cross section.

Starting from a pre-mining steady state flow system that represents the initial condition (Figure 4, cross section (a)), the simulation moves through a period of mining (Figure 4, cross sections (b), (c) and (d)), and concludes with a post-mining phase (Figure 4, cross sections (e) and (f)). As shown in Figure 4, the pattern of steady state flow before mining is predominantly lateral towards the left. During the mining phase,

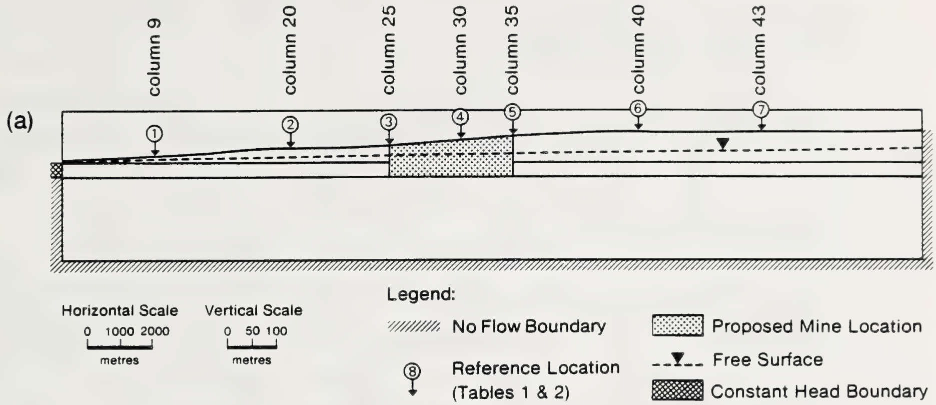
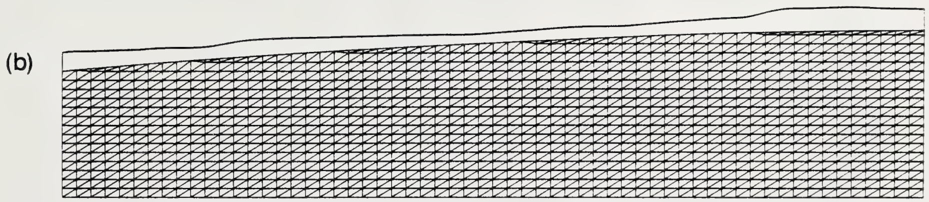
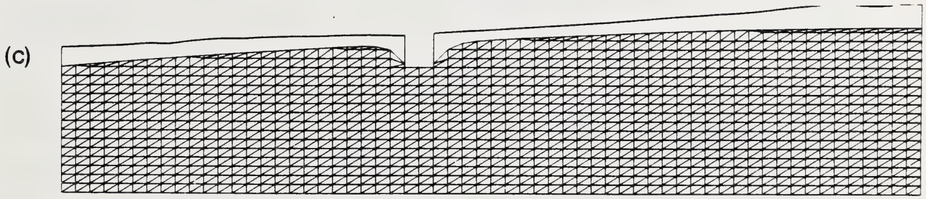


Fig. 3a. Cross section defining the large-scale, regional system of interest in this study. The circled numbers refer to positions along the water table that are referenced in tables 1 and 2



Pre-mining Steady State: Finite Element Grid

Fig. 3b. Example of the finite element grid generated to calculate the pre-mining steady state hydraulic head distribution.



First Mining Time Step: Finite Element Grid

Fig. 3c. Example of the change in the finite element grid due to mining and reclamation.

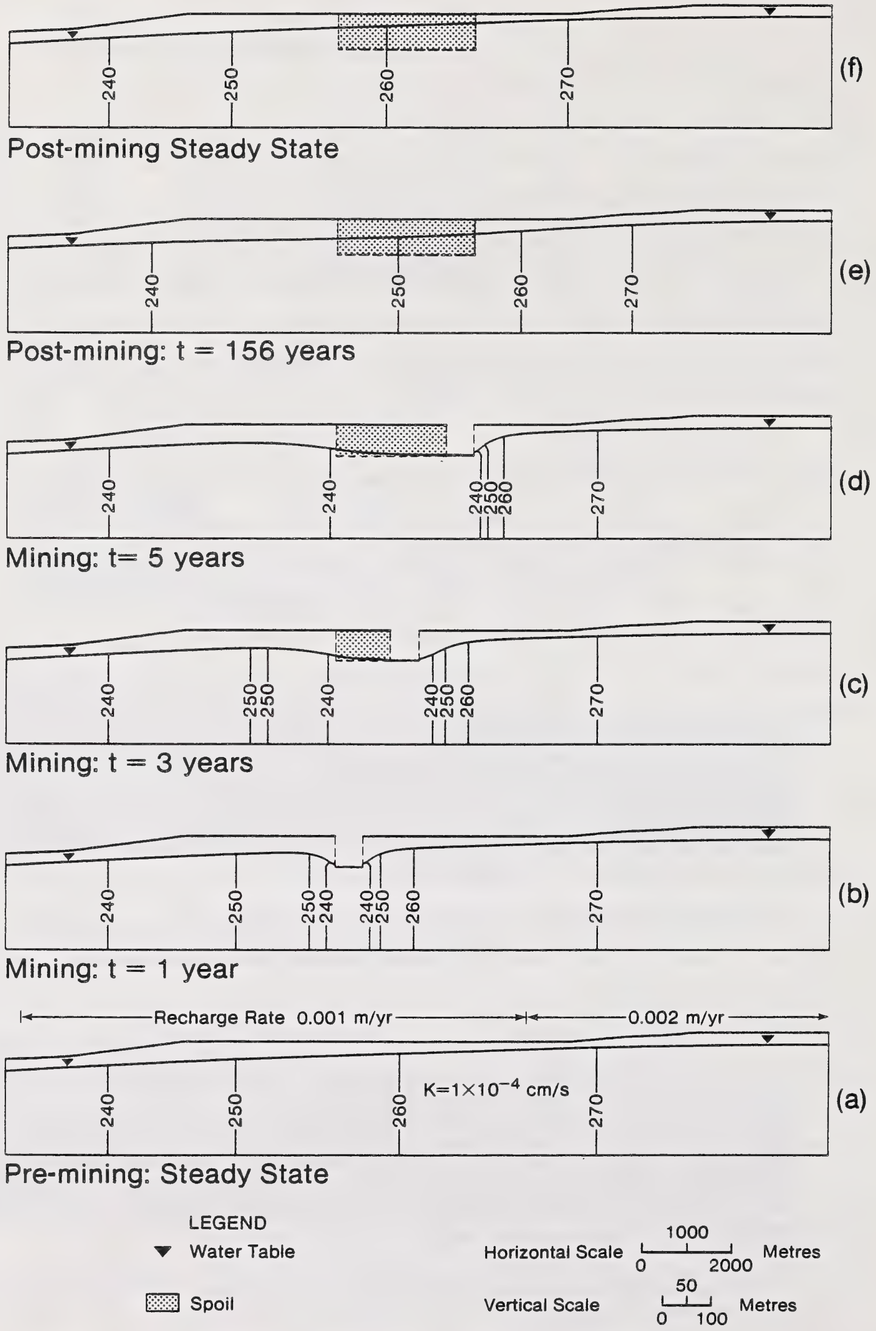


Fig. 4. Series of cross sections depicting the basic hydrogeological setting (a), and the distribution of hydraulic head at pre-mining steady state (a), during mining (b,c,d), following mining (e) and at the post-mining steady state (f).

the model simulates the opening of cuts, generates new cuts from left to right, and gradually increases the volume of spoil. This is shown in cross sections (b), (c) and (d) in Figure 4. The flow system adjusts constantly throughout the mining phase, discharging into the cut being mined, while the spoil begins to resaturate. After 6.5 years, mining is assumed to be complete and the last cut is filled. Note that water levels continue to change during the post-mining phase as the flow system returns to a new steady state as shown by cross section (f) in Figure 4.

Moving now to the detailed set of simulation results, we will examine how hydrogeological parameters, in relation to the mining, control changes in groundwater levels and the time over which these changes can develop on a regional scale. The scenarios studied in this section are:

1. Scenario R-1: local hydrogeological conditions;
2. Scenario R-2: mine landscape;
3. Scenario R-3: recharge rates through the spoil;
4. Scenario R-4: hydrualic conductivity of the spoil;
5. Scenario R-5: timing of post-mining water level responses.

2.1 LOCAL HYDROGEOLOGICAL CONDITIONS

This set of simulations, designated Scenario R-1, is designed to investigate how the hydrogeological setting outside of the mined area can control water level changes once mining has been completed. The first example (case R-1b) is an analysis of what happens to groundwater levels when a local discharge forms upstream of the mine. Such a discharge area could already exist before mining or actually form during the period of water level adjustment in the post-mining phase when a rising water table reaches the ground surface in a topographic low. In a second example (case R-1c), the influence of a surface water body in the vicinity of the mine is examined. In both cases, we compare the results of these simulations to case R-1a, which is a reference case where these local features have not been included (Figure 5a). In this way, it is possible to highlight changes in behaviour caused by changes in local hydrogeological conditions.

The geological setting for the three cases of this scenario consists of a thin unit with a hydraulic conductivity of $3x10^{-2}$ cm/s surrounded by a unit with a hydraulic conductivity of $1x10^{-3}$ cm/s. Both units are assumed to have a storativity of $5x10^{-4}$. The spoil is assigned a hydraulic conductivity of $1x10^{-4}$ cm/s and a storativity of $5x10^{-3}$. Recharge rates for the undisturbed region are 0.04 or 0.08 m/a. The rate

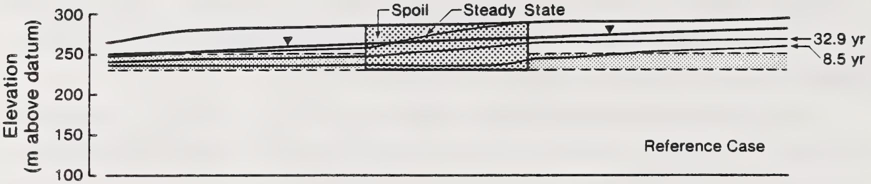


Fig 5a. A reference simulation showing changes in groundwater levels at various times in the post-mining period.

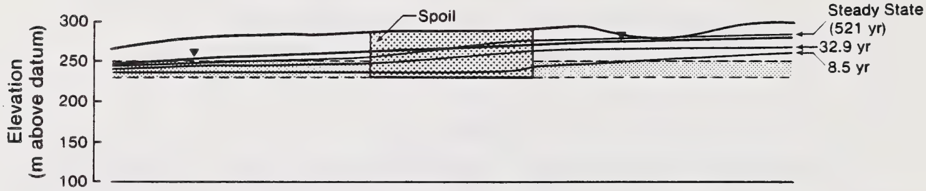


Fig. 5b. The response of water levels through the post-mining period to steady state when a topographic low is located adjacent to the mine.

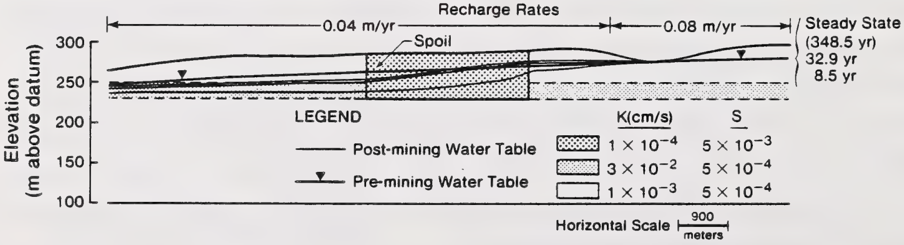


Fig. 5c. The response of water levels through the post-mining period to steady state when a water-filled depression is located adjacent to the mine.

through spoil is the same as the natural rate.

The configuration of the water table is presented across the domain from column 9 to column 51 of the grid. Equipotential lines are omitted because they usually tend to be vertical as a result of the very large exaggeration in scales and the lack of pronounced contrasts in hydraulic parameters.

For the reference case (case R-1a) at 8.5 years (Figure 5a), there has been a significant and widespread lowering of water levels as a consequence of mining. The main factor promoting such widespread drawdown is the relatively high hydraulic conductivity of the geological units. After 32.9 years, water levels are recovering and approaching the pre-mining steady state (Figure 5a). However, this water table position no longer represents the steady state. Water levels continue to rise to the new steady state position, which is characterized by a permanent water table rise upstream of the mine right up to the ground surface (Figure 5a). With the quantity of recharge added to the system remaining the same and the gross hydraulic conductivity of the system disrupted by the low permeability spoil, this response of the flow system is expected. Later analyses will focus on this aspect of system behaviour in more detail.

The first study compares the reference case to case R-1b, which has a topographic low situated upstream of the mine where it can promote the formation of a discharge area. The bottom of the topographic low is slightly less than 2 m above the position of the pre-mining water table (Figure 5b). The depression is assumed to be fully drained by a surface water system.

When the results of this simulation for the period of mining are compared to the reference case, there are no differences. Similarly, the pattern of water level recovery in the early post-mining phase (8.5 years, Figure 5b) is identical to that observed in Figure 5a. As before, water levels continue to rise (32.9 years) and the system eventually reaches a post-mining steady state (Figure 5b). A permanent rise in the upstream water table at steady state similar to that observed in the reference case (Figure 5a) does not develop here. The formation of a single discharge area in the topographic low controls the behaviour of the flow system and acts to offset the disturbance caused by mining to the extent that the steady state level after mining is only several metres higher than the pre-mining level. In effect, the impact of mining over the region is attenuated by a local topographic feature.

The second example (case R-1c) involves placing a pond in a depression located upstream of the mine (Figure 5c). It is assumed that the pond contains sufficient water to maintain a hydraulic head equal to the pre-mining water table elevation at the pond. Except for the presence of the pond, all other features of this system are identical to the reference simulation (Figure 5a).

In the early post-mining period (Figure 5c), the widespread drawdown upstream of the mine that is evident in the reference case (Figure 5a) does not develop. Induced infiltration from the pond during the period of mining has constrained the upstream spread of the zone of water level depression. Thus, water level changes during the period of mining will be less extensive than those observed in the reference case. The decline in water levels downstream of the mine is similar to that observed in the reference case.

The return of water levels to a post-mining steady state is strongly influenced by the presence of the pond. Once groundwater levels in the vicinity of the pond increase above the stage of the pond, the pond becomes a discharge area. Thus, when the flow system simulated in case R-1c finally reaches steady state, the position of the water table is very similar to that of the previous trial (case R-1b), and considerably lower than that observed for reference case (case R-1a).

These results provide more evidence of how a localized hydrogeologic feature can attenuate the kind of water table rise that is apparent in the reference simulation. The formation or existence of a local discharge area upstream of the mine inhibits the upward movement of the water table.

2.2 MINE LANDSCAPE

Previous simulations clearly demonstrate how the regional topography or ponds in the vicinity of a mine may control the long-term water table rise following mining. One important implication of this result is that a properly designed mine landscape may be effective in controlling water levels. Two slightly different post-mining landscapes (Scenario R-2) are tested in this section in order to evaluate their control on water levels. As before, the simulation results will be compared to a reference case (case R-2a), which for easier comparison has been repeated from case R-1a and is shown in Figure 6a. All other parameters of the simulation are identical to the reference case, case R-1a.

The first landscape, case R-2b, is one where the end cut is left open following the completion of mining. The actual location of the cut is depicted in Figure 6b. The open cut is assumed to be drained in such a way that any groundwater discharging into the pit is effectively removed via a surface drainage system. The response of water levels is not much different than the reference case for the first

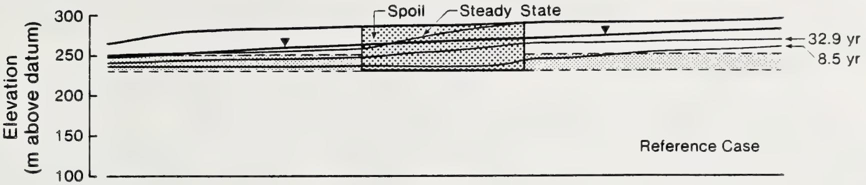


Fig. 6a. A reference simulation showing changes in groundwater levels at various times in the post-mining period.

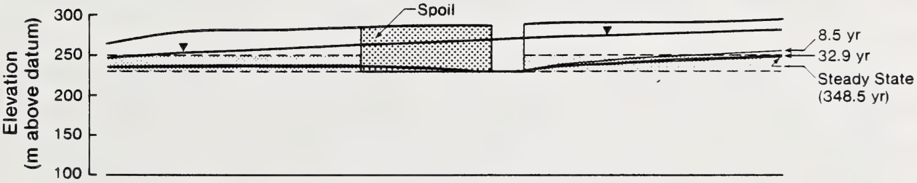


Fig. 6b. The response of water levels through the post-mining period to steady state when the end cut of the mine is open and able to drain.

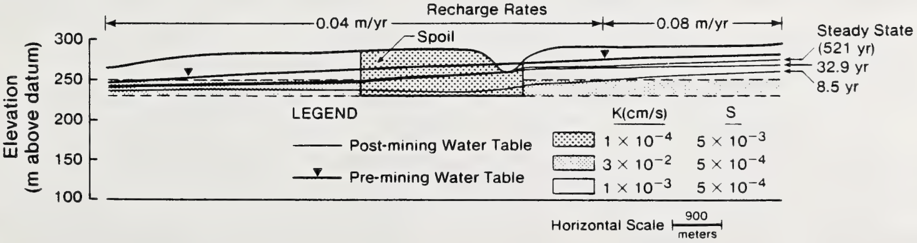


Fig. 6c. The response of water levels through the post-mining period to steady state when the end cut of the mine is partially filled and able to drain.

6.5 years of the simulations, because the mining procedure is identical. However, as shown in Figure 6b, water levels throughout the domain have declined during the early post-mining period because the last cut operates as a groundwater discharge area. Major differences between the two sets of results are noticeable at 32.9 years (compare Figures 6a and 6b). Keeping the last cut open continues to produce a decline in water levels. However, in the reference case, water levels are rising throughout much of the system and approaching the pre-mining steady state.

When this system reaches steady state, the final position of the water table is substantially lower than the pre-mining position (Figure 6b). As well, this pronounced lowering is spread across much of the domain. Landscaping the mine in this manner has resulted in a permanent water table decline on a regional basis. The extent of this decline is even more apparent when case R-2b is compared to the post-mining steady state for the reference case, case R-2a (Figure 6a). Thus, in case R-2b, the simple change in the manner in which the mine is landscaped has produced water level decreases ranging from approximately 45 to 51 m in the area upstream of the mine.

The second landscape, designated case R-2c, has the end cut partially filled and contoured (Figure 6c). Again, surface drainage removes all groundwater discharging into this depression. Examination of the results of case R-2c in Figure 6c shows that following mining there is the expected rise in the water table. When the water table rises to the elevation of the bottom of the depression, there is a constraint to a further significant rise in the water table. At steady state (Figure 6c), the post-mining water levels are again lower than the pre-mining levels. Relative to the reference case (Figure 6a), a permanent decline in water levels directly attributable to the mine landscaping is observed. However, this decline is not nearly as marked as when the last cut is left totally unfilled.

It is apparent from this pair of analyses that water levels on a regional scale can be influenced significantly by the landscaping of the spoil. Formation of a local discharge area does provide a constraint on the upward movement of the water table. However, it is important to note that the size of the area influenced by such a discharge area also depends on the hydraulic conductivity of the geologic units and the mine spoil. The relatively broad area of influence of the discharge areas in these two simulations is in fact related to the relatively high hydraulic conductivity of the units. If the hydraulic conductivity was less, the apparent decline in water levels would have been much more localized.

The results from cases R-2b and R-2c are also dependent on the complete surface drainage of the depressions. If for example, water is able to collect and form a pond in the depression, the response of regional groundwater levels could well be very different. While it is not possible to examine all scenarios in which the mine landscape can influence water level behaviour, the analyses portrayed here show that this parameter should be of importance in some circumstances.

2.3 RECHARGE RATES THROUGH SPOIL

There are indications from field studies that the rates of recharge to a groundwater system can be significantly altered when the geological regime is disturbed by strip mining (Rahn 1975; Miyamoto et al. 1977; Van Voast et al. 1977; Woessner et al. 1979; Lindorff 1980; Rehm et al. 1980; Hardaway 1981). The following group of simulations which form Scenario R-3 examine how changing the recharge rate through spoil can influence water levels. The basic hydrogeological system differs from the previous scenario. It has been simplified and now consists of a single geological unit with a hydraulic conductivity of 1×10^{-4} cm/s. The storativities of the spoil and undisturbed region are 5×10^{-3} and 5×10^{-4} respectively. The natural recharge rates are 0.001 and 0.002 m/a distributed as before with the highest rates applied upstream from the mine. The recharge rate through spoil is varied in three different simulations from 0.0001 to 0.001 to 0.005 m/a. The first of these recharge rates (case R-3a) is less than the natural rate and reduces the total post-mining recharge to 88% of the pre-mining rate. The second rate (case R-3b) is the same as the natural rate, which means that the total recharge to the system is the same before and after mining. The third case (case R-3c), with the highest rate, represents an increase in total recharge to 152% of the total pre-mining value.

The general response of water levels through the entire mining cycle for the 0.0001 m/a recharge case is essentially the same as that shown previously in Figure 4. Water levels around the mine decline during the period of mining and return to steady state following mining. Further inspection of this example will reveal an important feature of the water level response that has not been previously discussed. During the period of mining (Figures 4b, 4c and 4d), water table lowering is confined to the immediate vicinity of the area disturbed by mining. The maximum lowering occurs at the cut being mined and is controlled by the depth of mining below the water table. The zone of water table depression grows during mining as would be expected, and the water table in the spoil begins to recover once individual cuts are filled.

Significant lowering in water levels continues to the left or downstream from the mine even as the center of mining moves to the right and the water table rises in the spoil.

Moving next to the first of the post-mining sections (Figure 4e), it is surprising to see that the zone of water level lowering has continued to expand away from the mine. Within the spoil however, water levels rise. Thus, there are conditions where water levels in the vicinity of a mine can continue to fall although all mining activity has been completed. However, such a response is not observed in every case. This feature of water level response can last for as long as several hundreds of years in systems with low permeability receiving relatively small quantities of recharge. Water levels continue to fall once mining is complete, because the quantity of water flowing laterally to eliminate the hydraulic low that exists at the mine exceeds the rate at which recharge is being added. In more active flow systems, this behavior is not observed.

Ultimately the flow system returns to steady state in the post-mining period (Figure 4f). The system is characterized by a relatively small but widespread lowering of the water table compared to the pre-mining steady state.

When comparing simulation results for the three cases during mining, it is apparent that changing the recharge rate through spoil has only a minor impact on the pattern of water level lowering in the vicinity of the mine. The simulated position of the water table differs in these cases by less than 1 m. Apparently, these rates are not sufficiently different over such a relatively short period of time to produce significant changes to the degree of water table lowering.

The first important change in water levels becomes evident in a relatively early phase of the post-mining period. This phase, as was noted previously, is a period during which the area in which water levels are declining can grow. The series of results in Table 1 compares water level elevations at seven locations along the water table (refer to Figure 3 for specific locations). Location 4 is found in the middle of the mined area, Locations 3 and 5 are at the downstream and upstream boundaries of the mined area respectively, and Locations 1, 2 and 6, 7 are farther downstream and upstream of the mine respectively. To facilitate the comparison, the water levels are expressed as deviations from the pre-mining water table elevations. Although the differences among the simulated water table configurations are relatively small, the greatest water level declines are observed for case R-3a in which the recharge rate through the spoil is lowest (Table 1).

The magnitude of the deviation from the pre-mining values becomes smaller as the

Table 1. Deviation in water levels from the pre-mining steady state as a function of the recharge rate through the spoil.

Phase	Location Number[1]	Pre-mining Head in m	Deviation in m for Cases R-3a	R-3b	R-3c
Post-mining (156 years)	1	243.8	-4.9	-4.8	-4.3
	2	256.0	-11.2	-10.8	-9.4
	3	261.1	-13.9	-13.3	-11.0
	4	265.7	-15.3	-14.5	-11.9
	5	269.8	-14.2	-13.8	-12.0
	6	273.4	-11.2	-10.9	-9.9
	7	278.5	-5.2	-5.1	-4.8
Post-mining (steady state)	1	243.8	-1.7	0.0	+4.1
	2	256.0	-3.3	0.0	+7.9
	3	261.1	-4.0	0.0	+9.7
	4	265.7	-4.5	0.0	+10.5
	5	269.8	-4.6	0.0	+9.7
	6	273.4	-4.5	0.0	+6.6[2]
	7	278.5	-4.4	0.0	+7.9
Recharge Rate Through Spoil (m/a):			1×10^{-4}	1×10^{-3}	5×10^{-3}
Recharge Rate Downstream of Mine (m/a):			1×10^{-3}	1×10^{-3}	1×10^{-3}
Recharge Rate Upstream of Mine (m/a):			2×10^{-3}	2×10^{-3}	2×10^{-3}

[1] Refer to Figure 3a for locations defined by these numbers.
[2] Water table has reached the ground surface.

recharge rate increases (see cases R-3b and R-3c in Table 1). Thus, increasing the quantities of recharge passing through the spoil appears to reduce the impact caused by mining.

The second important change in water levels becomes apparent once the flow system has returned to steady state following mining. These effects are evident when the steady state results of all the cases in Table 1 are compared. For case R-3a the post-mining water table is slightly lower than the pre-mining water table in the downstream end of the system and from 4.4 m to 4.6 m lower upstream of the mine. For case R-3b there is no deviation, and for case R-3c the post-mining water table is markedly higher than the pre-mining water table, especially in the vicinity of the mine. These results are expected because the flow system must readjust to accomodate the change in the flow through the system. For example, when the overall recharge rates increase, the water table must rise to increase the gradient of flow in the system. Thus, the most significant impact on water levels, at the end of the simulation, is observed when the change of the recharge rate is greatest, which for these trials is when recharge through the spoil increases. The case of lowest recharge represents a small reduction in total recharge added to the system. As expected, and is shown for case R-3a, the regional decline in water levels caused by mining should not be very significant.

One general result of this latter analysis is that as a consequence of altering the recharge to the flow system, the post-mining configuration of the water table at steady state can differ markedly from the pre-mining configuration over relatively large areas. A decrease in the total recharge to the system will lower post-mining water levels, while an increase in the total recharge will raise water levels. The magnitude of the changes will depend on how significant the changes in recharge conditions are at the mine in relation to the total recharge to the flow system.

2.4 HYDRAULIC CONDUCTIVITY OF THE SPOIL

Another important disturbance caused by mining occurs when geological units are mined and replaced by spoil having a different hydraulic conductivity. The four simulations of Scenario R-4, presented in this section, are designed to examine how alterations to the hydraulic conductivity of spoil can contribute to changes in water level. Again, a non-layered geological system is considered. However, there are major differences in the model parameters compared to earlier cases. The geological unit is assumed to have a hydraulic conductivity of 1×10^{-2} cm/s, a storativity of

5×10^{-4}, and is recharged at rates of 0.1 or 0.2 m/a. Thus, this hypothetical system is much more active than any previous cases in terms of the quantity of water moving through the system. The pattern of flow before mining begins is, as before, generally lateral toward the left side of the domain.

The hydraulic conductivity of the spoil in these four cases is 1×10^{-4} cm/s; 1×10^{-3} cm/s; 1×10^{-2} cm/s; and 1×10^{-1} cm/s, respectively for cases R-4a, R-4b, R-4c and R-4d, which range from two orders of magnitude less than the pre-existing geological unit to one order of magnitude more. The storativity of the spoil and the recharge rate through the spoil are fixed at 5×10^{-3} and 0.1 m/a respectively. Thus, only the hydraulic conductivity of the spoil changes among runs.

The analysis will consider the behaviour of water levels at the end of the period of mining, relatively early during the post-mining phase (70.8 years), and at steady state during the post-mining phase.

After 6.5 years of mining, water levels differ by less than 1 m in all four cases. Just as in the previous scenario (Scenario R-3) where recharge rates are varied, time has not been sufficient for these differences in the hydraulic conductivity of spoil to influence water levels significantly.

The influence of spoil permeability starts to become important relatively early in the post-mining phase. Table 2 compares water level elevations at the same seven locations along the water table (refer to Figure 3). Also as before, water levels are defined in terms of the deviation in elevation from the pre-mining configuration of the water table. An examination of the results in Table 2 shows that the hydraulic conductivity of the spoil can have a significant impact on water levels in the vicinity of the mine and consequently the magnitude of water level lowering relative to the pre-mining condition. The greatest changes develop in the case of highest spoil conductivity (case R-4d) where at locations 5, 6 and 7, upstream of the mine, water levels are more than 6 m lower than case R-4a with the lowest hydraulic conductivity (Table 2). Downstream of the mined area, at locations 1, 2 and 3, differences are minimal with water levels for the case with the more permeable spoil being slightly higher than levels for the less permeable spoil.

Thus, at this early stage in the post-mining phase, the most significant drawdown is associated with spoils with the highest hydraulic conductivity. When the spoil is more permeable, the gross permeability of the flow system is increased and much smaller gradients in the system are required to move the fixed quantity of recharge. As the hydraulic conductivity of the spoil is decreased, there is less overall

Table 2. Deviation in water levels from the pre-mining steady state as a function of the hydraulic conductivity of the spoil.

Phase	Location Number[1]	Pre-mining Head in m	Deviation in m for Cases R-4a	R-4b	R-4c	R-4d
Post-mining (70.8 years)	1	243.8	-1.3	-1.3	-1.2	-0.9
	2	256.0	-2.5	-2.4	-2.2	-1.6
	3	261.1	-2.9	-2.7	-2.5	-1.8
	4	265.7	-2.0	-2.1	-2.9	-5.1
	5	269.8	-1.1	-1.4	-3.2	-7.9
	6	273.4	-1.4	-1.7	-3.4	-7.9
	7	278.5	-1.9	-2.1	-3.7	-8.0
Post-mining (Steady State)	1	243.8	0.0	0.0	0.0	0.0
	2	256.0	0.0	0.0	0.0	0.0
	3	261.1	0.0	0.0	0.0	0.0
	4	265.7	+1.5	+1.4	0.0	-3.1
	5	269.8	+3.0	+2.7	0.0	-5.9
	6	273.4	+3.0	+2.6	0.0	-5.8
	7	278.5	+2.8	+2.5	0.0	-5.7
Hydraulic Conductivity of Spoil: (cm / s)			1×10^{-4}	1×10^{-3}	1×10^{-2}	1×10^{-1}
Hydraulic Conductivity of Adjacent Units: (cm / s)			1×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-2}
Storativity of Spoil:			5×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-3}
Storativity of Adjacent Units:			5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}

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[1] Refer to Figure 3a for locations defined by these numbers.

drawdown relative to the pre-mining steady state system because water levels are increasing more rapidly in order to facilitate flow through the system.

Significant water level changes related to spoil permeability during the post-mining period are observed when the system is at steady state. The results (Table 2) follow an identical pattern that developed previously with changing recharge conditions through spoil. As shown in Table 2, when the spoil takes on the minimum value of hydraulic conductivity (case R-4a), there is a significant and permanent rise in water levels above the pre-mining steady state water table elevation. The change for case R-4a ranges from 0 m in the downstream end of the system to approximately 3 m upstream (Table 2). This increase in the gradient on the water table represents the response of the flow system to a decrease in the gross hydraulic conductivity of the system, while keeping the recharge to the system constant.

With spoil that is slightly more permeable (case R-4b), this effect is slightly less marked, increasing to a maximum of 2.7 m (Table 2). There is no difference between the pre-mining and post-mining water table configurations when the spoil has the same hydraulic conductivity as the single geological unit (case R-4c). When the hydraulic conductivity of the spoil is increased relative to the geologic unit (case R-4d), there is a permanent lowering of the water table following mining. This decrease ranges from 0 m to approximately 6 m, with the most significant changes upstream of the mine (Table 2). The regional gradient on the water table is reduced because water flows more efficiently in a system with a higher hydraulic conductivity.

A flow system will also be disturbed significantly when a permeable unit is replaced by spoil with a lower hydraulic conductivity. This effect develops in the steady state results shown in Figure 5a. Destroying the continuity of very permeable geologic units represents a much more severe disturbance than that observed previously because the overall hydraulic conductivity of the flow system has the potential of decreasing significantly. The most pronounced, permanent rise in regional water levels will be generated when a single, highly permeable unit is eliminated by mining. If only one of several units is affected or the most permeable units are not disturbed, the rise in water levels will be less significant.

2.5 TIMING OF POST-MINING WATER LEVEL RESPONSES

Any characterization of water level change is not complete without studying the time over which these changes develop. The time period following mining is most important in this respect because of the obvious implications for the regulation of mined-lands. If, for example, the full extent of water level changes does not develop until years after the site is abandoned, environmental problems may be slow to develop.

In Scenario R-5, we use two different groups of several simulations to evaluate the time required for changes in the post-mining water levels to be completed and to identify key controlling parameters. The simulations in case R-5a are based on a single geological unit with a hydraulic conductivity of 1×10^{-4} cm/s and relatively low natural recharge rates (0.001 and 0.002 m/a). The hydraulic conductivity of the spoil and recharge rate through the spoil are the same as those for the undisturbed system. The simulations included in case R-5b also involve a single geological unit but with a hydraulic conductivity of 1×10^{-2} cm/s, relatively high natural recharge rates (0.10 and 0.20 m/a), a recharge rate through spoil of 0.10 m/a and spoil permeabilities ranging from 1×10^{-1} to 1×10^{-4} cm/s.

Comparing the times required for these systems to reach steady state, it is apparent that the greatest differences occur between the groups rather than within any one case. For the simulations in case R-5a, typically many tens of thousands of years are required for the systems to reach steady state. For the simulations in case R-5b, times to reach steady state range from 775 to 1166 years. These results suggest that increasing the hydraulic conductivity of the geological unit and natural recharge rates by two orders of magnitude reduces the time for the system to reach steady state by approximately two orders of magnitude. Other results not presented here for a group of simulations with parameters intermediate between those for cases R-5a and R-5b support these conclusions.

These results show just how variable the timing of post-mining changes in water levels can be. It appears that the recovery in water levels following mining depends in part upon how efficient the groundwater system is in moving water to the potential low caused by the mining. Very long times are required for the system with the lowest natural recharge rate and hydraulic conductivity to respond. When the flow systems are considerably more active such as those in case R-5b simulations, a faster post-mining response for the system is observed.

Another parameter that should exert some control on the timing of water level changes in transient flow systems is storativity. The next series of simulations (case R-5c) will examine the extent to which water level recovery in the post-mining period is influenced by the storativity of the mine spoil. The basic system to be evaluated is identical to that depicted in Figure 5a. The storativity of the mine spoil is varied in three separate trials from 5×10^{-2} to 5×10^{-3} to 5×10^{-4}.

Changing the storativity of the spoil over a range of three orders of magnitude significantly influences the timing of water level changes. As expected, the higher the storativity value, the slower the water levels change. Thus, as the storativity of the spoil increases from 5×10^{-4} to 5×10^{-3} to 5×10^{-2}, the time required for post-mining steady state to be achieved increases from 342 to 515 to 1165 years, respectively.

One surprising result of the analyses presented in this section relates to the relatively long times that can be required for the post-mining readjustment of a flow system to take place. Such results coincide with observations made by Toth (1978) who found that in regional flow systems with low hydraulic conductivities transient readjustments in flow patterns may require many years. In view of our study, such a situation is undesirable because impacts related to mining may not develop until several hundreds of years following the abandonment of the site.

The results from these simulations are not totally generalizable. The relatively long times for flow system readjustments are also related to the basic design of the simulations. In the absence of local hydrogeological features similar to those discussed earlier in this section, water level changes have the opportunity to be propagated far from the mine over relatively long times. In most situations, local features of the hydrogeology effectively attenuate the changes in water level, making it possible for the system to return to steady state more rapidly.

3. MINE-SCALE SIMULATIONS

What we will examine in this chapter is how the model can be used to examine the process of spoil resaturation at the mine-scale. The position of the water table and its changing configuration with time depends in general upon the ability of the flow system to provide internal drainage and the character of recharge that is applied to the system. These characteristics of groundwater flow are controlled in the model through the choice of values of hydraulic conductivity and recharge rate. Using a series of sensitivity analyses, we will show how these parameters control spoil resaturation. In particular, the parameters selected for detailed examination include:

1. Scenario M-1: hydraulic conductivity of the spoil;
2. Scenario M-2: hydraulic conductivity of adjacent geological units;
3. Scenario M-3: recharge rates through the spoil, areal distribution;
4. Scenario M-4: recharge rates through the spoil, pond locations;
5. Scenario M-5: recharge rates through the spoil, pond depth;
6. Scenario M-6: interaction between variables, hydraulic conductivity of the spoil and recharge rates;
7. Scenario M-7: interaction between variables, hydraulic conductivity of adjacent geological units.

All the following figures that accompany these scenarios only show the region between columns 9 and 51 because this is the region of interest, corresponding to the mine, in this chapter.

Depicted in Figure 7 is a schematic representation of the flow domain and boundary conditions for the mine-scale problem. Before mining begins, it is assumed that there is no recharge to the system and the water table is flat. All subsequent recharge is assumed to enter the flow system only through the mine spoil. The bottom boundary is considered to be no-flow while constant hydraulic heads are assigned to nodes along the side boundaries. As an initial condition, all interior and constant head nodes are assigned hydraulic head values of 170 m (relative to a local datum), which also are equal to the elevation of the water table. This initial condition is simpler than that used in the previous section because the necessity of actually solving for the pre-mining, steady state distribution of hydraulic head is avoided. All of the simulations in this section are based on storativity values of 5×10^{-3} for the spoil and 5×10^{-4} for the geological units.

As was the case in earlier trials, mining is simulated over a 6.5 year period beginning at the left side of the mine and proceeding to the right in a series of steps.

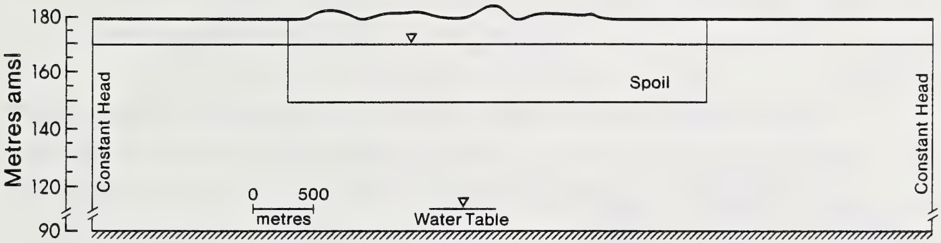


Fig. 7. Schematic representation of the flow domain for the mine-scale problem illustrating the zone disturbed by mining, the boundary conditions and the initial water table configuration.

As each successive cut is opened, the preceeding one is filled with spoil. The post-mining phase of the simulation begins when the last cut is filled with spoil. Although hydraulic head data are calculated during each time step of the actual period of mining, our analyses will be concerned with detailing the pattern of spoil resaturation once mining has ended. All of the figures will depict the position of the water table during this phase, starting with the configuration just before the end cut is closed.

3.1 HYDRAULIC CONDUCTIVITY DISTRIBUTION

The first part of this analysis focuses on whether the hydraulic conductivity of spoil influences spoil resaturation. Shown in Figure 8 are the conditions for Scenario M-1 where only the hydraulic conductivity of the spoil is varied, from 1×10^{-4} to 1×10^{-5} to 1×10^{-6} cm/s in cases M-1a, M-1b and M-1c, respectively. Recharge is applied to the spoil at a uniform rate of 0.02 m/a. The hydraulic conductivity is 1×10^{-5} cm/s in the particular unit in which the mine is developed.

The position of the water table in these three simulations is shown at 6.5 years, immediately before the end cut is filled, and later at 12.1, 24.8, 36.2 and 53.3 years. Comparison of the results for times of 24.8 years and earlier shows no significant differences among the three cases (Figure 8). The range in differences does not exceed 1 m. Thus, the resaturation of the spoil in this case is not sensitive to the hydraulic conductivity of the spoil. Such results imply that the pattern of water table rise is governed by external factors such as the relatively uniform pattern of water level recovery outside of the mine and uniformly distributed recharge. Other simulation results not presented here show that there are certain geological conditions where the hydraulic conductivity of the spoil can exert somewhat more control over the pattern of water level recovery in geological units around the mine. The best example of this effect is when high hydraulic conductivity units are truncated by the spoil. However, even in these cases the effect is not marked.

During the final stages of spoil resaturation (Figure 8), the pattern of water level response in the spoil changes significantly. At 53.3 years, water levels in the three cases differ by as much as 4.5 m. At this time, the water table in the spoil is at a higher elevation than the water table in the geological unit adjacent to the spoil. Discharge areas also begin to form at topographically low positions in the spoil. When this situation develops, the hydraulic conductivity of the spoil becomes much more

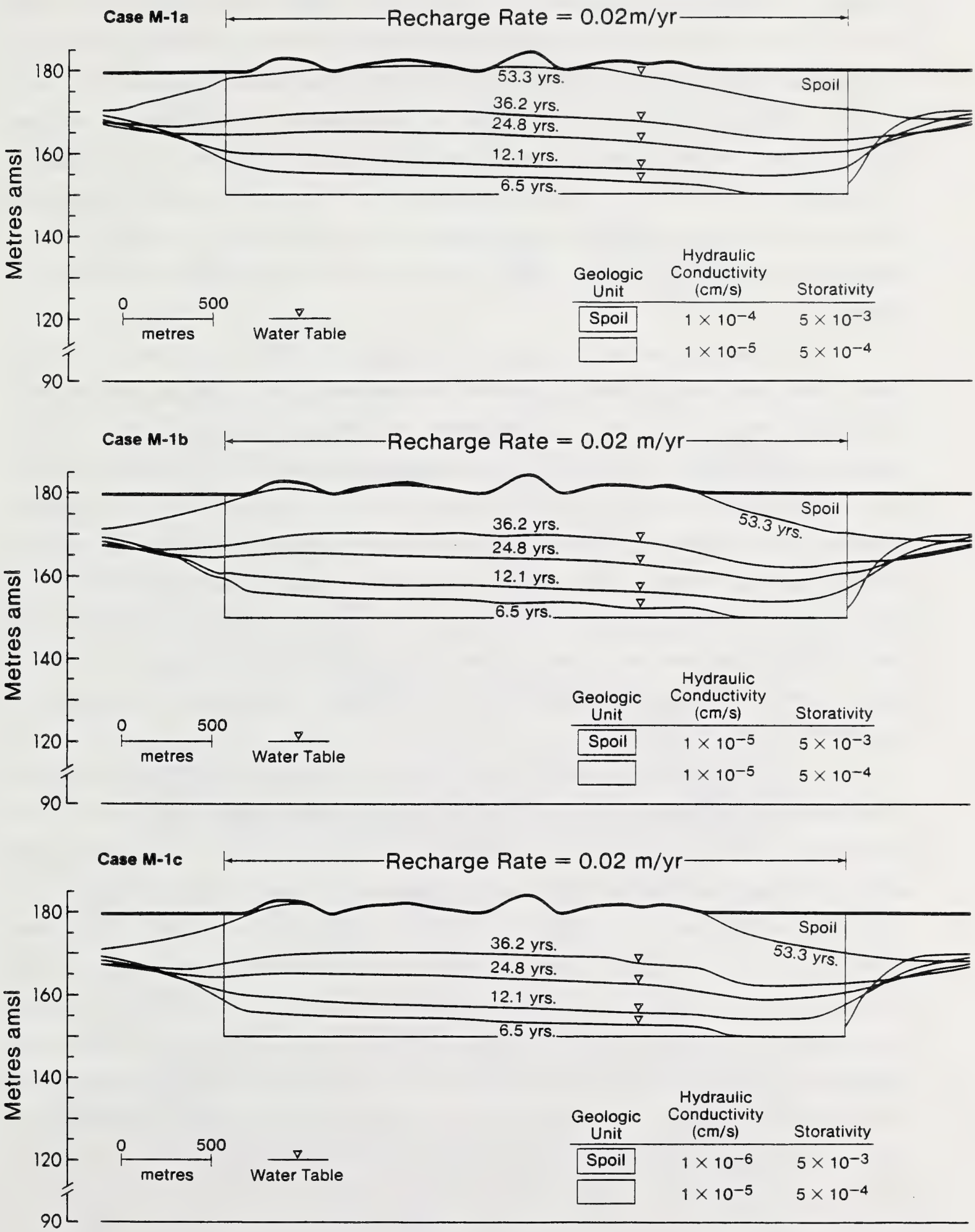


Fig. 8. The pattern of spoil resaturation as a function of the hydraulic conductivity of the spoil.

important in controlling the extent of further water level rise. Clearly, when the hydraulic conductivity of the spoil is very low, as in case M-1c, the configuration of the water table coincides closely to the ground surface because the local flow system in the spoil is not efficient in moving water to the sides of the flow domain or local discharge areas within the spoil. As the hydraulic conductivity of the spoil increases, as in cases M-1b and M-1a, the water table does not rise everywhere to the ground surface (ie. case M-1a) because a combination of a high hydraulic conductivity and a relatively low hydraulic gradient is able to move the quantity of recharge applied to the system.

In the next scenario, M-2, our examination of hydraulic conductivity shifts now to geological units outside of the mine. The series of four cases we will compare are the same (Figure 9) except for the pattern of geological layering. Case M-2a is a single layer case where the geologic unit is assigned a hydraulic conductivity of 1×10^{-5} cm/s. Cases M-2b and M-2c are both characterized by a single unit with a higher hydraulic conductivity of 3×10^{-4} cm/s surrounded by units with a lower conductivity of 1×10^{-5} cm/s. The only difference between these trials is that in case M-2c the higher hydraulic conductivity layer is thicker and extends beneath the mine (Figure 9). Case M-2d is a five layer case where a zone of very high hydraulic conductivity passes below the mine. The most permeable unit in this group of three layers has a hydraulic conductivity of 3×10^{-3} cm/s.

Results for this series of cases (Figure 9) show the important role played by the hydraulic conductivity of unmined units in controlling spoil resaturation. As a general rule, more permeable units adjacent to the mine promote much more rapid water table rise at early times. Compare, for example, the water table position at 12.2 years in cases M-2a and M-2d. With an increase in hydraulic conductivity for the given lateral boundary conditions, lateral inflows of water to the spoil increase with increasing hydraulic conductivity. Also apparent in Figure 9 is a change in the way water levels respond once continuing recharge to the spoil raises the water table in the spoil higher than surrounding areas. For cases M-2c and M-2d during times later than 24.8 years, the presence of relatively permeable units adjacent to the mine essentially halts significant increases in water levels above levels prevailing in the vicinity of the mine. The geological units have sufficient permeability to efficiently transmit the natural recharge to the sides of the domain under a relatively small gradient in hydraulic head. For cases M-2a and M-2b, the water table must rise much more significantly to transmit the recharge through low conductivity geological units to the constant head

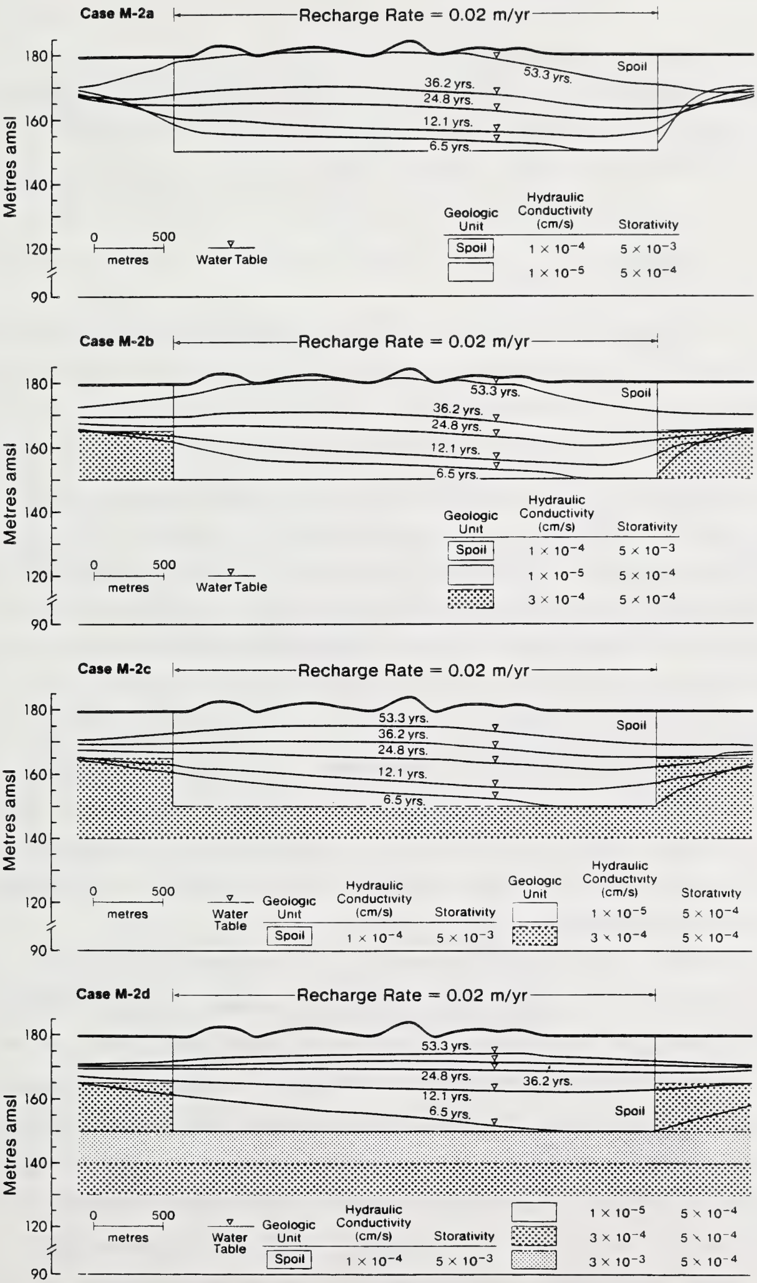


Fig. 9. The pattern of spoil resaturation as a function of the hydraulic conductivity distribution outside of the mine.

boundaries at the sides of the flow region.

3.2 VARIATION IN RECHARGE RATES

The objective of this section is to evaluate how spoil resaturation is influenced by variability in recharge rates. With the first set of simulations (Scenario M-3), we will look first at simple systems where the actual quantity of recharge through the spoil is constant temporally and spatially for a given trial. Later we will concentrate on systems where recharge related to ponds can vary as a function of position within the spoil (Scenario M-4)

The conditions for Scenario M-3 are depicted in Figure 10. Hydraulic conductivity values of 1×10^{-4} and 1×10^{-5} are assigned to the spoil and single geologic unit respectively. Again for all the simulations in this section, the spoil and geological unit(s) are assigned storativity values of 5×10^{-3} and 5×10^{-4} respectively. Recharge rates for the three cases, M-3a, M-3b and M-3c are 0.200, 0.020 and 0.005 m/a respectively, applied to the spoil. Looking in general at the results in Figure 10, we note that significant changes in time scales are apparent from case to case suggesting that for this problem, spoil resaturation is very sensitive to recharge rate. With the highest recharge rate (case M-3a), the spoil resaturates extremely rapidly with the water table reaching the ground surface within 3 or 4 years following mining. By decreasing the recharge rate in cases M-3b and M-3c, we note that considerably more time is required in general for the spoil to resaturate. For example in case M-3c, this time ranges to as much as several hundreds of years. This sensitivity of water levels in the spoil to recharge rates is also related to the low hydraulic conductivity of the geological unit around the mine. Lateral inflow to or from the spoil, for example in case M-3a, has a very limited influence on water levels.

As before, there is an important change in the character of the water table configuration once the spoil system begins to act as a recharge area. For example, in case M-3a, the water table rises to the ground surface because with a recharge rate of 0.200 m/a, this relatively low permeability system can only respond by increasing the hydraulic gradients to the maximum extent. Once the water table reaches the ground surface, the boundary conditions change at appropriate nodes from constant fluxes to constant heads, effectively reducing the recharge rate for this case. In the low recharge case (case M-3c), the water table approaches the ground surface much more slowly and it could be possible for a configuration to be developed below the ground surface, which is compatible with the ability of the flow system to move this quantity

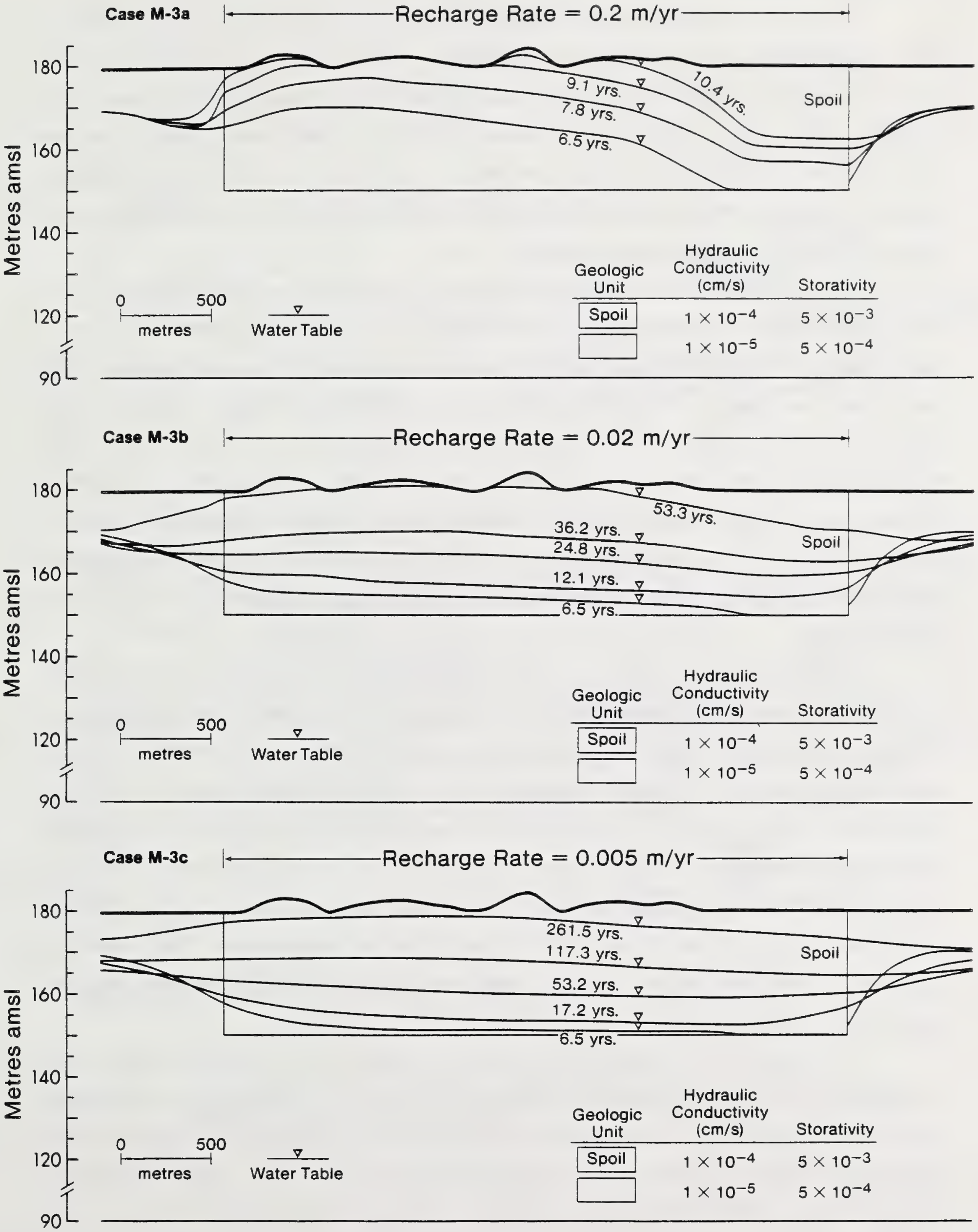


Fig. 10. The pattern of spoil resaturation as a function of the recharge rate through spoil.

of recharge applied to the system.

The simulations of Scenario M-4 illustrate the role of surface ponds in spoil resaturation. In the first pair of simulation trials (Figure 11) recharge to the system is concentrated either at one (case M-4a) or two (case M-4b) ponds in the system, where leakage totals approximately 0.47 m/a at each pond. Away from the ponds recharge through the spoil is assumed to be 0.020 m/a. As in the previous scenario (Scenario M-3), the spoil is assumed to be somewhat more permeable than the undisturbed geological unit (Figure 11).

The important influence of ponds in controlling the configuration of the water table in spoil is apparent in the results shown in Figure 11. Increased recharge due to leakage from ponds results in pronounced mounding of the water table beneath the ponds. The rate at which the mound grows and the magnitude of the hydraulic gradient is directly proportional to the quantity of leakage from the pond. Eventually, the water table rises to the bottom of the pond and the leakage rates from the bottom of the pond are substantially reduced because of the change in boundary conditions from constant flux to constant head nodes. From this point in time onward, the spoil saturates more slowly at least in cases where the hydraulic conductivity of the spoil is relatively small.

The change in boundary conditions can play an important role in controlling the manner in which the spoil resaturates. The following results from simulations in Scenario M-5 highlight how the bottom elevation and standing head of water in a pond are important variables in determining when the change in boundary conditions occurs. Case M-5a, shown in Figure 12, is identical to the single pond case shown in Figure 5. The pond bottom has a relative elevation of 1128.5 m and for simplicity a standing head of 168.5 m. In cases M-5b and M-5c (Figure 12), the bottom of the pond is placed at relative elevations of 171 m and 174 m respectively. The remaining parameters characterizing the recharge rates and hydraulic conductivity are similar to those used in Scenario M-4.

From an examination of the results in Figure 12, it is apparent that the rate of spoil resaturation is related to the elevation of the pond bottom. For early times, there are no differences in the results because the rates are identical. Once the water table reaches the pond with the lowest elevation (case M-5a, Figure 12) differences in the water table configuration become apparent. For example, compare the water table positions at 24.8 and 36.2 years in cases M-5a and M-5c. When the pond is at the highest elevation (case M-5c), leakage can continue at the maximum rate for a longer

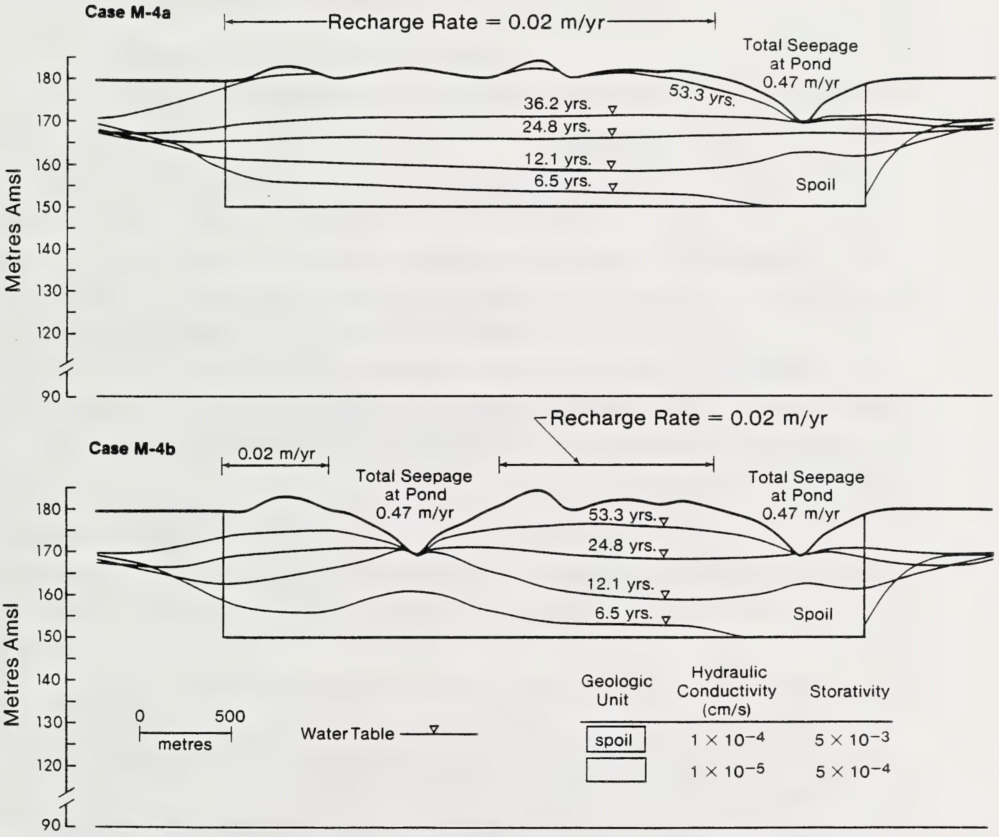


Fig. 11. Variation in water table responses as a consequences of recharge through ponds.

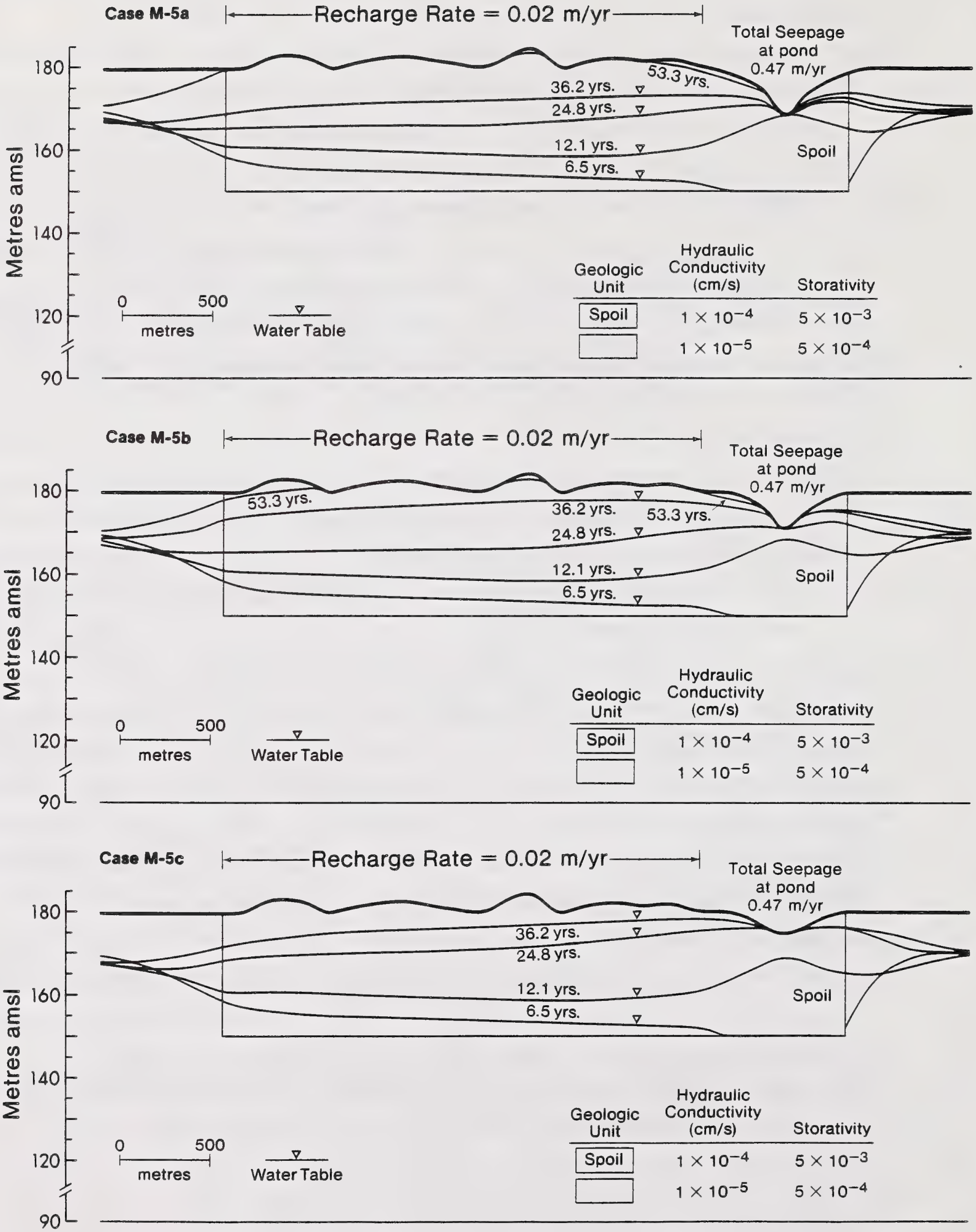


Fig. 12. The pattern of spoil resaturation as a function of the elevation of a pond in the spoil landscape.

time. The net result is a much more rapid rise of the water table. At 53.3 years, the results can not be compared because in case M-5b this time step is missing and in the other trials the numerical solution loses resolution as the water table interacts simultaneously with the ground surface across the majority of the mine. We can conclude from these simulations that the relative position of the ponds in the mine landscape can be important in controlling the rate at which the spoil resaturates.

3.3 INTERACTIONS BETWEEN VARIABLES

Up to this point, there has been a detailed examination of the interactions between variables such as recharge rate and hydraulic conductivity. Actually, the experimental design necessary for fully evaluating these interactions would require a prohibitively large number of simulation trials for a rigorous assessment. Detailed work of this kind is clearly beyond the scope of the present study. What we would like to do here is to demonstrate that effects due to the interaction of variables exist and may be important in generating different responses.

The results of earlier simulation trials showed that for early times following mining, the pattern of spoil resaturation was generally insensitive to the hydraulic conductivity of the spoil. In Scenario M-6 (Figure 13) two cases are compared that differ from each other only in terms of spoil permeability. However, they differ from the earlier cases in the way recharge is added. The hydraulic conductivity of spoil in cases M-6a and M-6b have respective values of 1×10^{-4} and 1×10^{-5} cm/s. Recharge is assumed to come primarily from two surface ponds (Figure 13).

The simulation results for these trials show significant differences in the manner in which the spoil resaturates. During the early portion of the simulation, the groundwater mounds beneath the ponds are higher and have much steeper gradients when the spoil has a low hydraulic conductivity (case M-6b), than those in more permeable spoil (case M-6a). These differences relate to the increased difficulty that groundwater has in flowing in the lower permeability spoil relative to the more permeable system.

Thus, the main reason why the earlier simulations showed the hydraulic conductivity of the spoil to be an insensitive variable is because of the choice of uniform recharge for those simulations. It appears that the hydraulic conductivity of the spoil can become important in controlling the pattern of spoil resaturation whenever conditions are such that significant hydraulic gradients develop within the

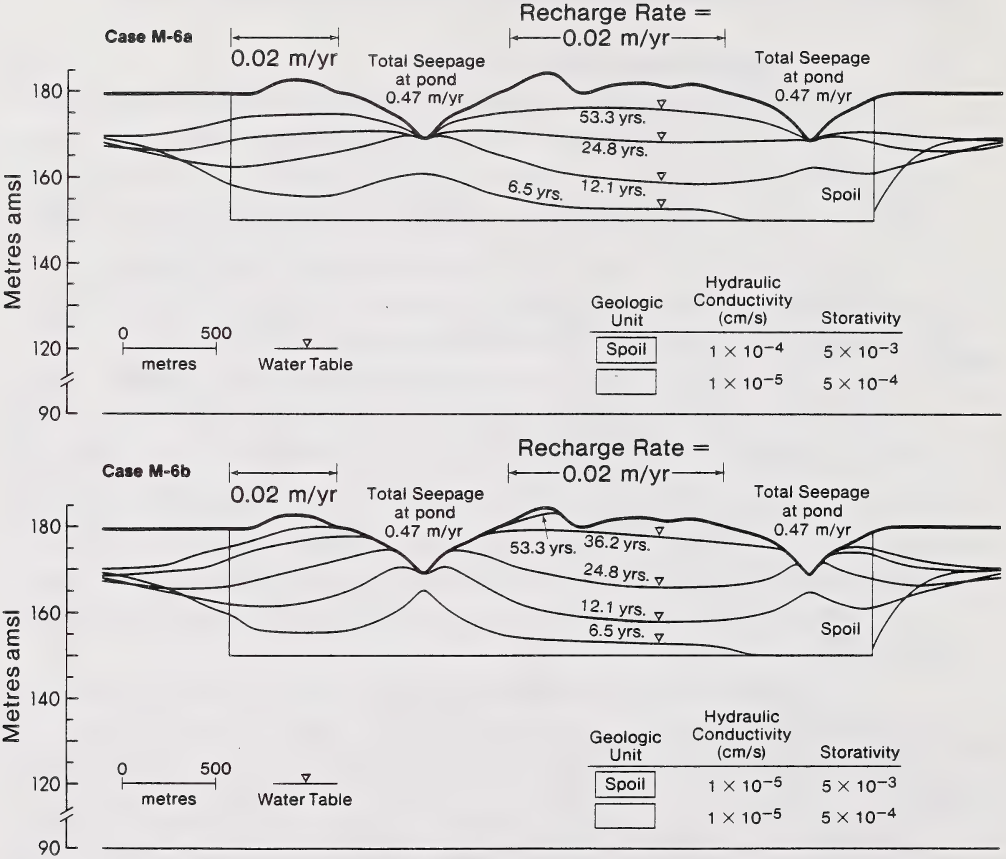


Fig. 13. The pattern of spoil resaturation as a function of interactions between the hydraulic conductivity of the spoil and recharge varying spatially.

spoil.

Scenario M-7 examines whether an interaction between recharge through ponds and geological layering produces any significantly different results than observed earlier. This analysis considers three different geological settings with recharge for earlier times coming from two surface ponds. Case M-7a is identical to case M-4b where a spoil with a hydraulic conductivity of 1×10^{-4} cm/s is surrounded by a single geological unit with a hydraulic conductivity of 1×10^{-5} cm/s. Cases M-7b and M-7c are based on the three and five layer configurations depicted in Figure 14. As before, the setting with five layers represents a case where a high hydraulic conductivity zone is placed beneath the mine.

The addition of geologic layers to enhance hydraulic conductivity appears to have an important influence on the pattern of spoil resaturation at earlier times. In case M-7a and to a lesser extent in case M-7b, resaturation is characterized by mounds that form beneath the ponds, reflecting the non-uniform distribution of recharge. In case M-7c, where significant permeability exists in units beneath the spoil, mounding is minimal. The units with the high hydraulic conductivity are able to efficiently redistribute recharge thereby reducing the gradients along the water table. For example, at times greater than 36.2 years, it is apparent that the units beneath the spoil with a high hydraulic conductivity (case M-7c) operate to reduce the water table rise observed between the ponds from that of the case which lacks this highly permeable zone (case M-7a).

This examination of the character of interactions between variables has shown how these effects can be important in significantly altering behavior determined from a simple parametric analysis. In general, it becomes relatively difficult to develop general concepts to characterize the response of the water table in spoil. The pattern of spoil resaturation is a complex one dependant upon a variety of parameters such as hydraulic conductivity, recharge rates and the interaction of these parameters.

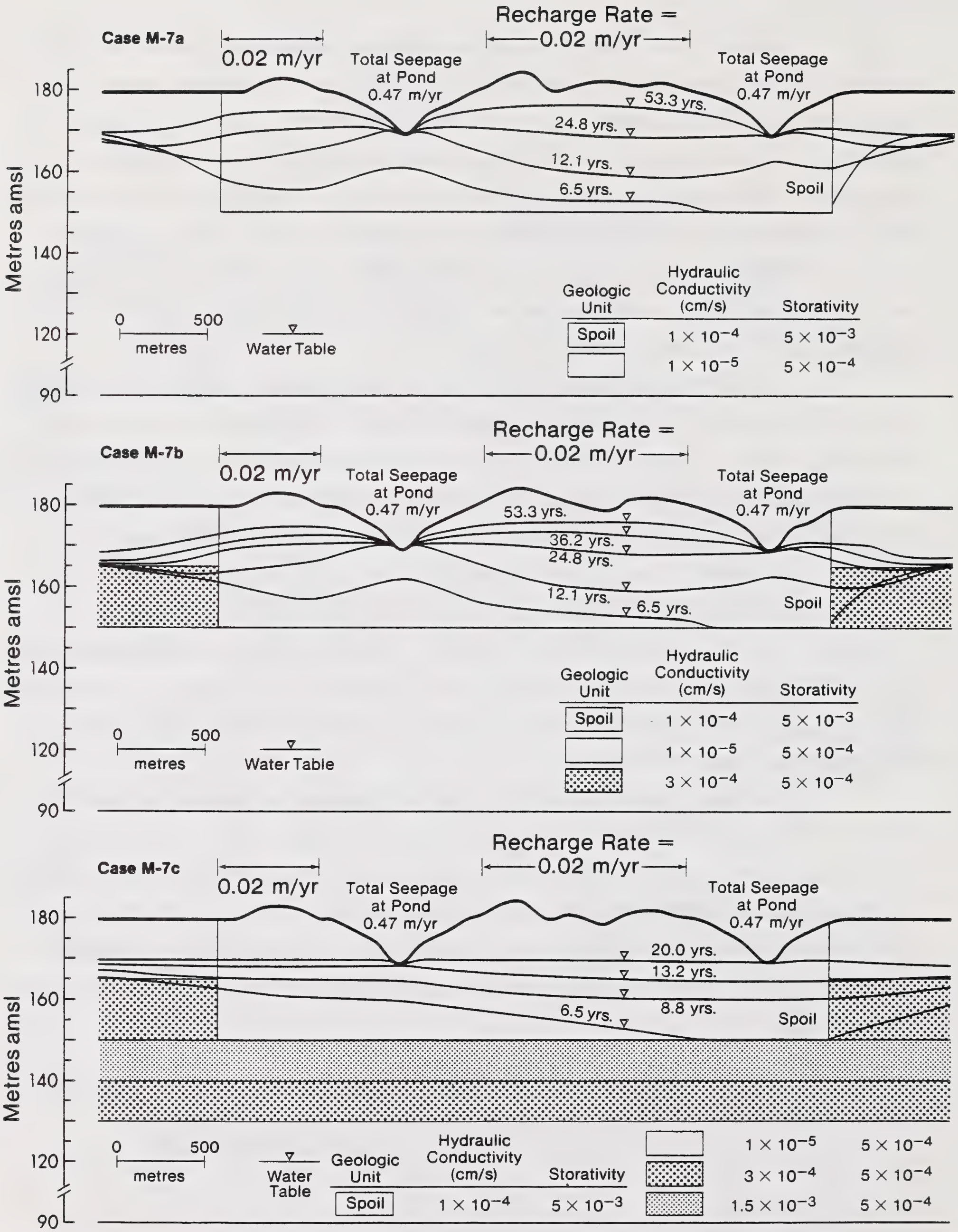


Fig. 14. The pattern of spoil resaturation as a function of interactions between the hydraulic conductivity of geological units and the recharge rate through spoil.

4. HILL-SCALE SIMULATIONS

This section presents the results of sensitivity analyses on factors that influence the steady state configuration of the water table at a local scale. The basic landscape element of interest is a hill formed from spoil during the reclamation phase of the mining operation. Not only do these analyses provide insight on the behaviour of the recovery of the water table following reclamation, they also provide a conceptual guide to reclamation strategies.

All the simulations presented in this section are based on a two-dimensional cross section comprised of a symmetrical hill constructed from spoil. Although the general shape remains the same throughout all of the cases, features of size, hydrogeology and drainage vary from case to case. The topographic features of the hill that are examined include the slope of a hill, the height of the spoil and the width at its base. The general shape of the hills can be divided into two groups. The first group, illustrated in Figure 15, has a constant height of 20 m but a variable base of the hill of 860 m, 430 m and 215 m, which corresponds to slopes of 5%, 10% and 20%. The second group of hills have a constant width at their base of 215 m, but variable heights of 2 m, 5 m, 10 m and 20 m, corresponding to slopes of 2%, 5%, 10% and 20%, respectively (Figure 16). Hydrogeological parameters are specified for each case and include the hydraulic conductivity of the spoil, the recharge rates, and the hydraulic conductivity of the subsurface drains, if they are present.

In order to simplify the presentation of the analyses, only the steady state configuration of the water table is provided. The initial conditions for these cases assume that water table is horizontal with a relative elevation of 97.5 m. The finite element grid is regular, except along the water table, and initially consists of 61 columns and 17 rows. Once recharge is applied to the system, the water table begins to rise within a hill and continues to do so until either a steady state is reached or the water table intersects the surface of the hill. The simulations presented in this section involve four different sensitivity analyses on the following parameters of interest:

1. Scenario H-1: covariation of hydraulic conductivity of the spoil and the hill shape;
2. Scenario H-2: covariation of recharge rates through the spoil and hill shapes;
3. Scenario H-3: variation in the position of local surface discharge areas;
4. Scenario H-4: variation in the type and spacing of drains.

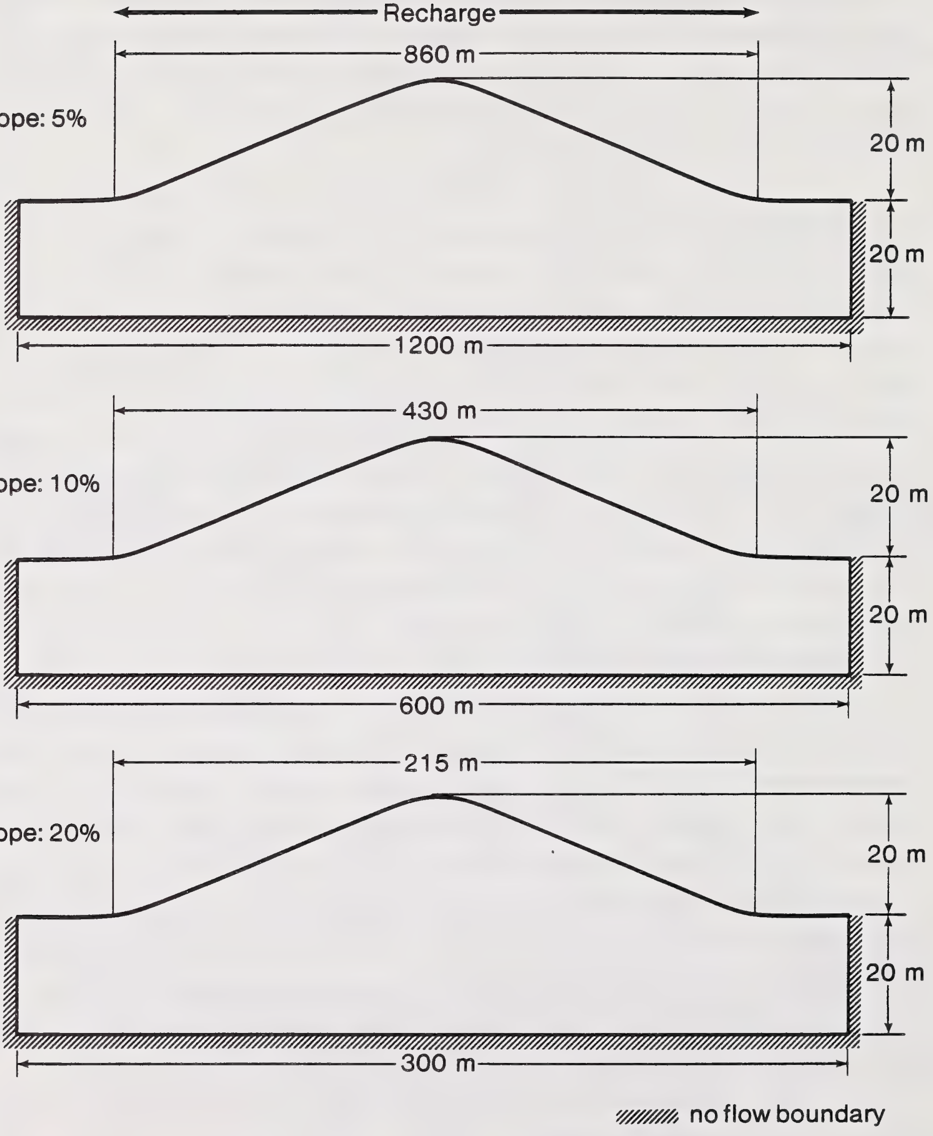


Fig. 15. Schematic illustration of the hills with varying base widths but constant heights of 20m..

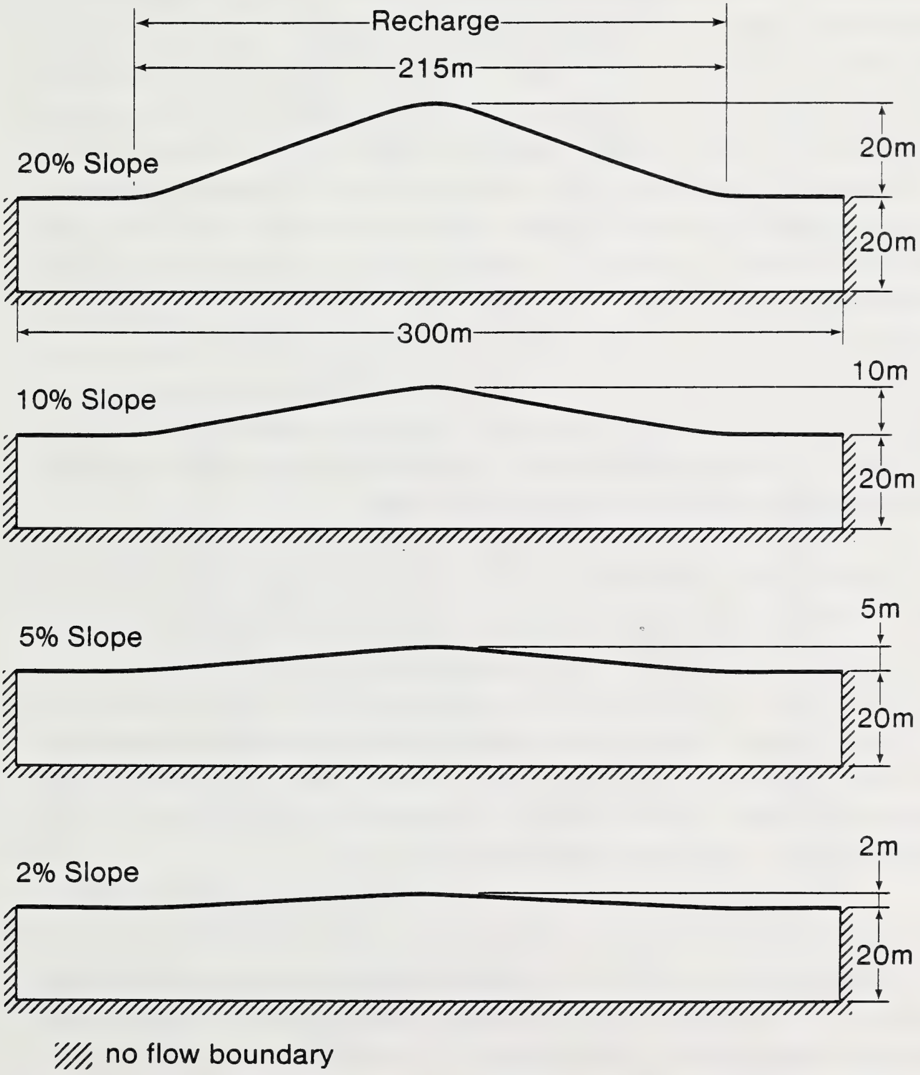


Fig. 16. Schematic illustration of the hills with varying heights, but constant base widths of 215m.

4.1 HYDRAULIC CONDUCTIVITY OF THE SPOIL

The first scenario (H-1) is designed to show how the hydraulic conductivity of the spoil together with the shape of the hill controls the distribution of hydraulic head within a flow system, and hence the position of the water table at steady state. Two groups of hills are used in the study of the influence of the hydraulic conductivity of spoil on the position of the water table with hills. The first two cases of Scenario H-1 involve three hills (illustrated by Figure 15) with a constant height of 20 m and widths at their base of 860 m, 430 m and 215 m. Two latter cases make use of the four hills that are shown in Figure 16, having a constant width of 215 m and heights of 2 m, 5 m, 10 m and 20 m. While the value of storativity has no bearing on the steady state configuration of the water table, it is required here because the simulations are transient, proceeding through several time steps to steady state in order to ensure that any interaction of the water table and the ground surface is handled correctly. The storativity of the spoil is fixed for all four cases at 5×10^{-4}. In all simulations, a surface depression, 2.5 m deep, acts as a groundwater discharge area and is situated at the left side of the hill at its base.

The differences in the elevation of the water table at steady state for case H-1a, with a hydraulic conductivity of 1×10^{-5} cm/s, in the three hills are depicted in Figure 17. The maximum elevations of the water table under the centre of the hills are listed in Table 3. As the slope of the hill increases from 5% to 10% to 20%, the rise in water table becomes successively less in each case (Table 3). This rise ranges from 7.8 m (5% slope) to 1.4 m (20% slope). The water table intersects the ground surface only at the base of the three hills on the right side. Hence, with a relatively high hydraulic conductivity, as in this example, groundwater is able to drain from the spoil and prevent the hill from becoming substantially saturated.

In Scenario H-1b, the value of the hydraulic conductivity is lowered to 1×10^{-6} cm/s. Results are again portrayed in Figure 17 and the maximum elevation of the water table listed in Table 3. These results show that recharge drains relatively slowly from this spoil and allows the water table to rise within the hill. The rise of the water table ranges from 6.0 m (20% slope) to 20.2 m (5% slope). The configuration of the water table is modified by the slope of the hill. In case H-1b, with a hydraulic conductivity of 1×10^{-6}, cm/s the water table rises to the ground surface along both sides of the hill with a 5% and 10% slope.

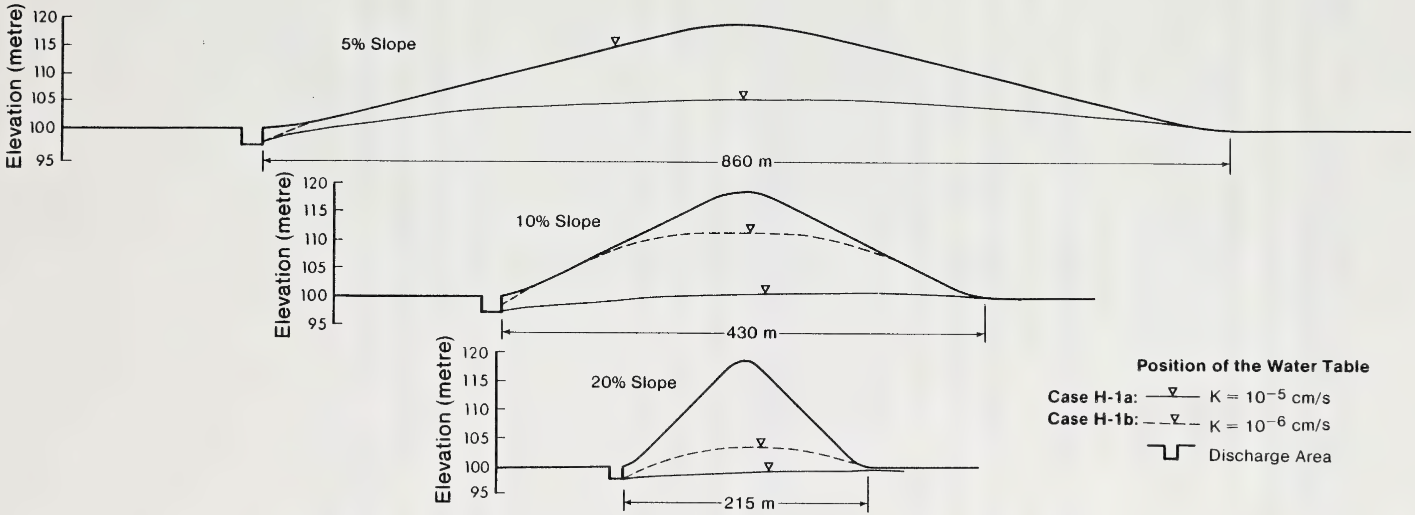


Fig. 17. Position of the water table in hills having a constant height of 20 m as a function of hydraulic conductivity.

Table 3. Elevation of the water table beneath the peak of the hills as influenced by the hydraulic conductivity of the spoil.

	Elevation of the Water Table for Cases			Change[1]
	Initial	H-1a	H-1b	
Slope of 5%:	97.5 m	105.3 m	117.7[2] m	12.4[2] m
Slope of 10%:	97.5 m	100.8 m	111.8 m	11.0 m
Slope of 20%:	97.5 m	98.9 m	103.5 m	4.6 m
Hydraulic Conductivity:		1×10^{-5} cm/s	1×10^{-6} cm/s	
Storativity:		5×10^{-4}	5×10^{-4}	
Recharge Rate:		0.005 m/a	0.005 m/a	

[1] Change = (H-1b) - (H-1a)

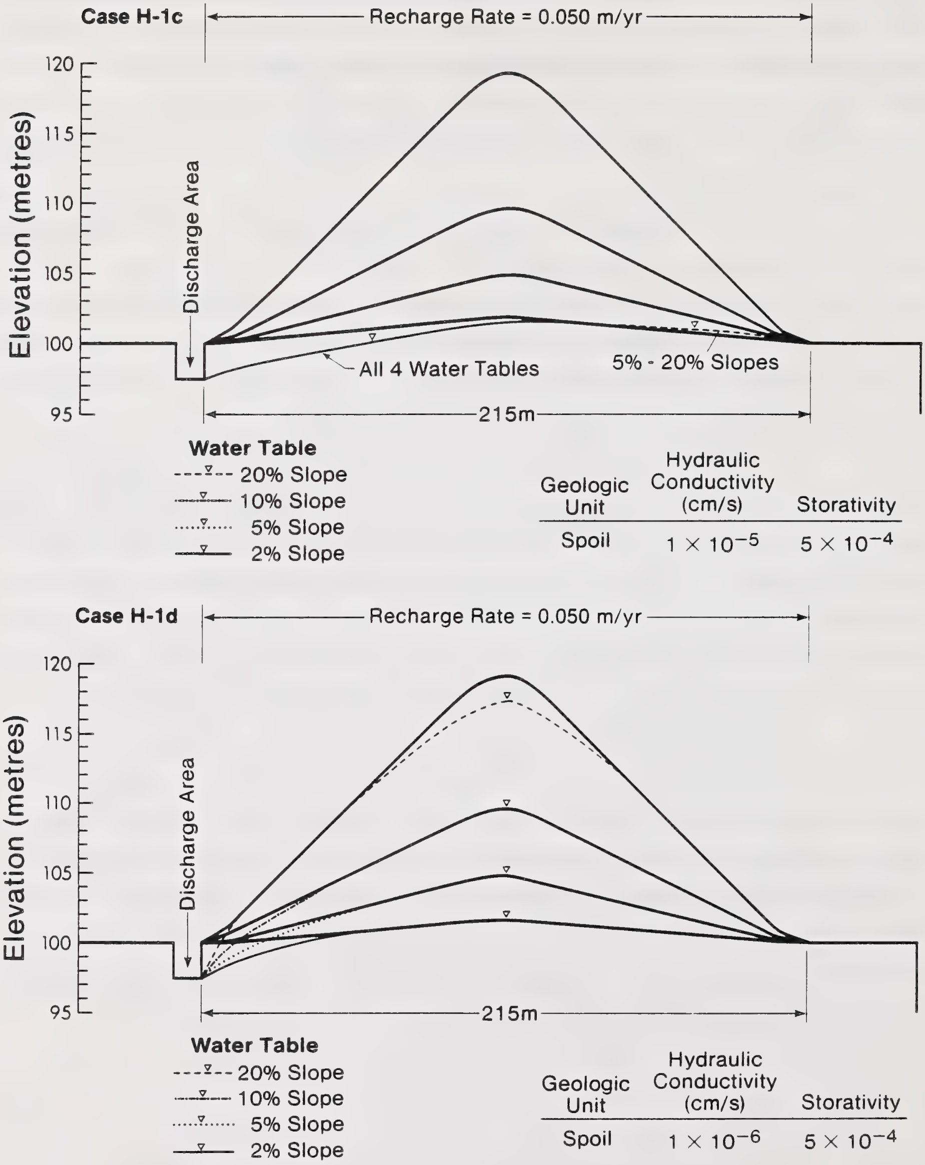
[2] The water table has reached ground surface over the entire hill.

Comparing the three simulations of case H-1a (hydraulic conductivity of 1×10^{-5} cm/s) with those of case H-1b (hydraulic conductivity of 1×10^{-6} cm/s) shows that as the hydraulic conductivity is decreased, the elevation of the water table within the hill at steady state increases. The change in water levels from the starting value is 430% higher in the case with lower hydraulic conductivity as compared to the change for the higher conductivity situation. Because the water table in the hill with a slope of 5% can only rise as high as the ground surface, the change is only 260%. It is expected that the position of the water table would be considerable higher if the ground surface had not been intercepted.

The next two simulations of Scenario H-1 are designed to show the effect of changing hydraulic conductivity from 1×10^{-5} cm/s (case H-1c) to 1×10^{-6} cm/s (case H-1d) in the hills with a constant width but variable height. These hills, illustrated in Figure 16, are 230 m wide at the base and vary in height from 2 m to 5 m to 10 m to 20 m, as the slope varies from 2% to 5% to 10% to 20%. The recharge rate is higher (0.050 m/a) than used in cases H-1a and H-1b.

As in the previous set of runs, as hydraulic conductivity decreases, the water table rises (Figure 18). However, because the distance to the discharge area is relatively short, water is rapidly drained from the hills that have a high hydraulic conductivity (case H-1c). But as the hydraulic conductivity decreases, as in case H-1d, the water table rapidly rises because the flow system can only adjust to the fixed quantity of recharge by changing the hydraulic gradient. Thus resulting in the water table intersecting the ground surface along most of the sides of the hills (Figure 18).

Even with an evaluation using only two values of hydraulic conductivity, 1×10^{-5} cm/s and 1×10^{-6} cm/s, it is evident that the hydraulic conductivity is an important parameter that controls the position of the water table at steady state. As hydraulic conductivity decreases, even by only one order of magnitude, the elevation of the water table increases significantly because drainage is restricted. In all hills composed of spoil characterized by a low hydraulic conductivity, the water table eventually rises to intersect the ground surface and cause groundwater seepage problems along a significant portion of the slope.



Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-5}	5×10^{-4}

Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-6}	5×10^{-4}

Fig. 18. Position of the water table in hills having a constant base width of 215m, as a function of hydraulic conductivity.

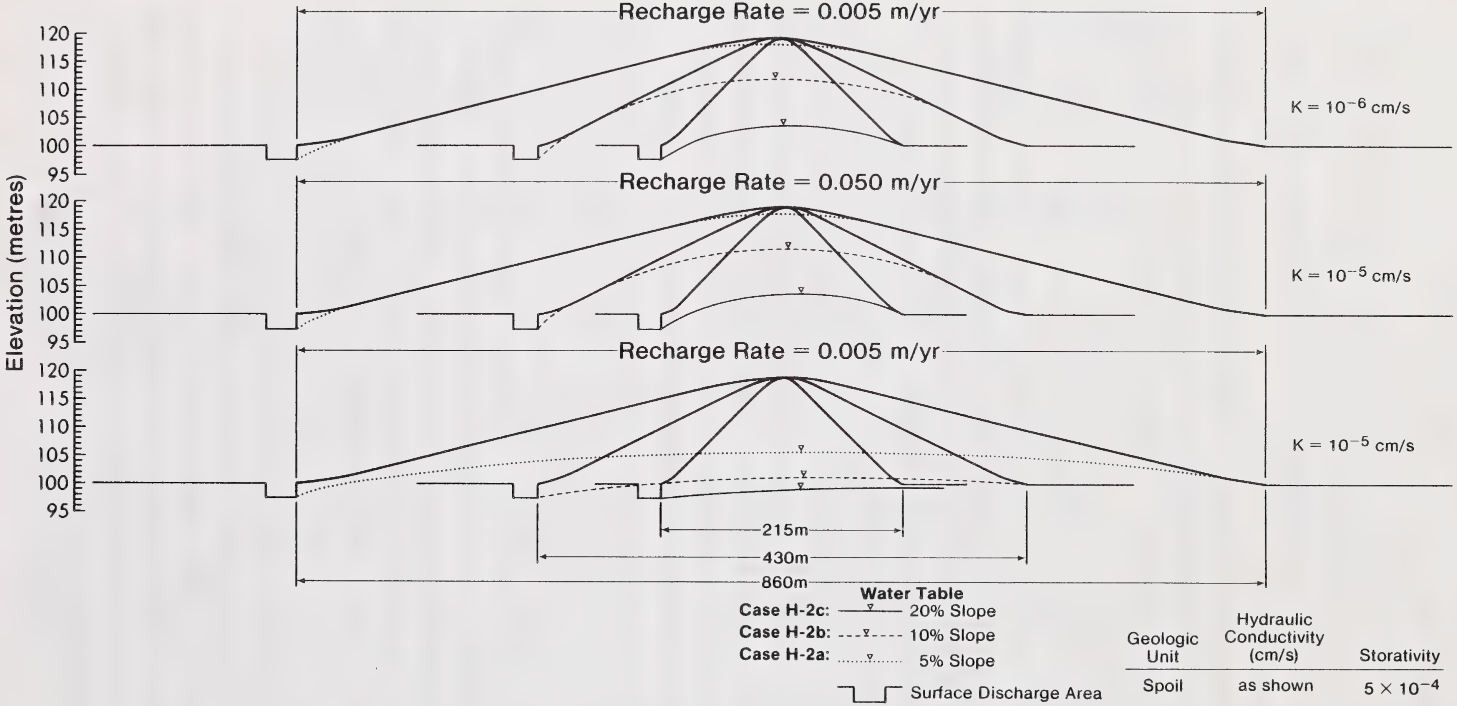
4.2 SHAPE OF THE HILL

The shape of the reclaimed hill is controlled by the extent of landscaping at a particular site. With minor landscaping, the hills will be relatively high and narrow, and have steep slopes. With major landscaping, the hills will be broad and relatively low, and have gentle slopes.

Scenario H-2 uses two groups of hills to aid in understanding how the design of the landscaping influences position of the water table as it recovers in the spoil. In order to simplify the analyses, only the base or the height (and hence the slope) of the hill changes during each trial. The first set of simulations involves the series of hills illustrated in Figure 15. These hills have a constant height of 20 m, but the slopes vary from 5% to 10% to 20%, resulting in a change in width of the base from 860 m to 430 m to 215 m, respectively. The second group of simulations involves hills with a constant width at the base of 215 m, and heights of 2 m, 5 m, 10 m and 20 m, corresponding to slopes of 2%, 5%, 10% and 20% (Figure 16).

The first three cases are conducted with the hills having a constant height and variable base. These cases are case H-2a, H-2b and H-2c corresponding to hills with slopes of 5%, 10% and 20%. The hydraulic conductivity and recharge rate varied among the three cases, however, storativity is fixed at $5x10^{-4}$. The sets of hydraulic conductivity and recharge that are simulated are, (a) $1x10^{-6}$ cm/s and 0.005 m/a, (b) $1x10^{-5}$ cm/s and 0.050 m/a, and (c) $1x10^{-5}$ cm/s and 0.005 m/a.

The results of these simulations, illustrated in Figure 19, show that in all cases as the slope decreases (and hence the width of the base increases), the elevation of the water table at steady state increases. The magnitude of this rise for these various cases under the differing conditions of hydraulic conductivity and recharge rates is summarized in Table 4. The results indicate that as the slope of the hill is doubled the rise in the water table from the initial water level is slighly less than half of rise of the preceeding slope. When hydraulic conductivity is $1x10^{-5}$ cm/s and the recharge rate is 0.005 m/a, for example, the decrease in the water table between cases H-2a and H-2b is 4.5 m, or a 236% change from the initial position of the water table. The decrease in the elevation of the water table between cases H-2b and H-2c is 1.9 m, or again a 236% change. However, as the slope decreases, under conditions of low hydraulic conductivity or high recharge, the water table rises to the ground surface along a major portion of the sides of a hill having a relatively low slope (case H-2a). It is expected that should the water table have been able to freely rise without intersecting the slope of the hill and forming a groundwater discharge zone, the extent



Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	as shown	5×10^{-4}

Fig. 19. Position of the water table in hills having a constant height of 20m, base varies from 215m (20%) to 430m (10%) to 860m (5%) wide, as a function of the shape of the hill.

Table 4. Elevation of the water table beneath the peak of the hill as influenced by the height and width (slopes) of hill.

	Water Table Elevation in m for Cases				% Change Between	
	Initial	H-2a	H-2b	H-2c	a - b[1]	b - c[2]
Slope of the Hill:		5%	10%	20%		
(a) $K=1x10^{-6}$ cm/s: Storativity=$5x10^{-4}$ Recharge=0.005 m/a	97.5	117.7[3]	111.8	103.5	-----[3]	238%
(b) $K=1x10^{-5}$ cm/s: Storativity=$5x10^{-4}$ Recharge=0.050 m/a	97.5	117.7[3]	111.8	103.6	-----[3]	235%
(c) $K=1x10^{-5}$ cm/s: Storativity=$5x10^{-4}$ Recharge=0.005 m/a	97.5	105.3[3]	100.8	98.9	236%	236%

[1] % Change = (H-2a - Initial)/(H-2b - Initial)
[2] % Change = (H-2b - Initial)/(H-2c - Initial)
[3] The water table has reached ground surface.

of the rise of the water table would be comparable. The change of the position of the water table within hills of varying slopes can be explained in two ways. First, as the base of the hill increases, the length of a flow path to a discharge area increases. Hence with a given hydraulic conductivity and recharge rate, the gradient and final water table elevation will be greater for a hill with a large base (small slope) than for a hill with a short base (high slope). Second, while the total recharge per unit width of the hill remains constant, the total volume of water entering the hill increases as the hill becomes wider. Thus, more water must be drained from the spoil.

The second group of simulation trials uses the hills with a constant width at their base but with varying heights (Figure 16). The hills have slopes of 2%, 5%, 10% and 20%, corresponding to cases H-2d to H-2g. The recharge rate is 0.050 m/a and the storativity of the spoil is 5×10^{-4} in all four cases. However, the four cases are simulated with hydraulic conductivities of 1×10^{-6} cm/s and 1×10^{-5} cm/s.

These simulations produces very different results from the previous three cases. For the hills that have a relatively high hydraulic conductivity (1×10^{-5} cm/s), the water table rises by approximately 3 m in all four cases (Figure 18). Simulations with hills that have a low hydraulic conductivity (1×10^{-6} cm/s), indicate that as the water table rises it intersects the ground surface everywhere (except in the immediate vicinity of the local discharge area) for cases H-2d, H-2e and H-2f, and along the majority of the ground surface for case H-2g (Figure 18).

The results of these latter four cases would indicate that the rise of the water table is independent of the slope of the hill if the base of the hill remains constant. A controlling factor appears to be the length of the flow path from the centre of the groundwater mound to a discharge zone. Given equal hydrogeological conditions, the elevation of the water table increases with an increasing width of the hill at its base. The slope of a hill becomes important as a rising water table intersects the surface of the hill, causing groundwater seepage, and reducing the amount of water available to form a groundwater mound.

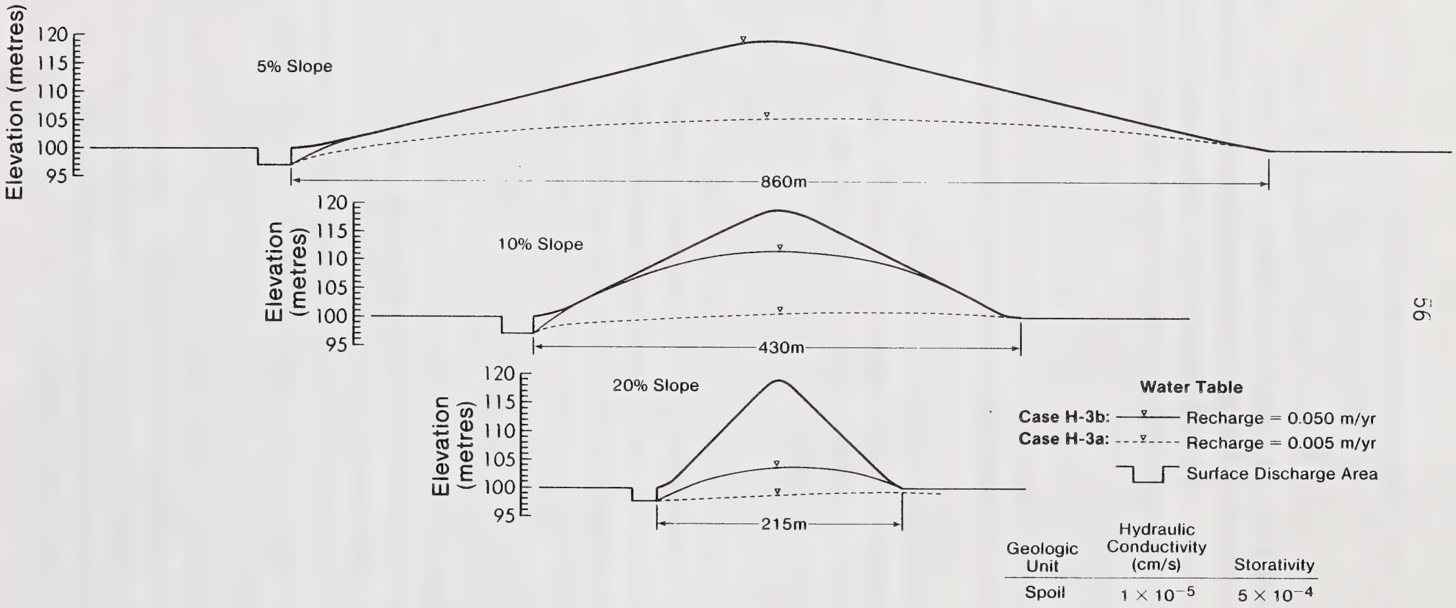
The results observed here are in part due to the nature of the model, which applies recharge directly to the water table and does not consider seepage through the unsaturated zone. However, it is expected that with equal recharge rates among all hills, these results can be extrapolated to real situations. We were not able to study two other effects related to the topography of a hill that can influence the position of the water table. However, they are worth identifying as a possible point of departure in future studies. First is the general observation that steeper slopes increase the quantity of surface runoff, thereby reducing the total recharge to the groundwater system. Second, should surface depressions exist on a hill, water could accumulate and produce localized zones of high groundwater recharge.

The results of the analyses studying the effects of changing the topography of the hill indicate that, from a hydrogeological point of view, the width of the hill is the principal factor controlling the elevation of the water table. By increasing the width of the hill, more water enters the spoil and the length of the flow path to a discharge zone increases, thus causing high water levels. The only effect that the height and slope of the hill have is in influencing the total length of the surface that ultimately will become waterlogged. On steeper slopes, there is much less tendency for the water table to rise to the ground surface than on more gentle slopes.

4.3 RECHARGE RATES THROUGH THE SPOIL

This scenario, H-3, is designed to study how various recharge rates through the spoil can influence the position of the water table. Two recharge rates were applied to the spoil, a relatively low rate of 0.005 m/a (case H-3a) and a higher rate of 0.050 m/a (case H-3b). The shape of the hills used in this analysis are the same as those in the previous scenarios. They are assumed to have slopes of 5%, 10% and 20% (Figure 15) corresponding to a width at the base of 830 m, 430 m and 215 m. The height of all three hills is 20 m. The spoil is assigned a hydraulic conductivity value of 1×10^{-5} cm/s and a storativity of 5×10^{-4} for the two cases.

A comparison of the two cases, presented in Figure 20, indicates that with all parameters constant but the recharge rate, which increases from 0.005 m/a in case H-3a to 0.050 m/a in case H-3b, the final elevation of the water table increases. For example, looking at the results of the hill with a slope of 20%, an increase of 1.4 m above the initial elevation of the water table is observed for case H-3a, and an increase of 6.0 m is observed for case H-3b (Table 5). This results in a net change between case H-3b and H-3a of 4.6 m (438%). A similar pattern is observed within the hill with a 10% slope. Here, the water table rise between case H-3b and H-3a is 3.3 m and 14.3 m, respectively, or a change of 11.0 m (433%). Thus, it appears that regardless of the slope of the hill, increasing the recharge rate by one order of magnitude leads to an increased water table elevation of approximately 430% from its initial position. The change in the elevation of the water table in the hill having a 5% slope would be about the same magnitude but because the water table reaches the ground surface no further rise is possible (Figure 20).



Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-5}	5×10^{-4}

Fig. 20. Position of the water table in hills having a constant height of 20m, as a function of recharge rates.

Table 5. Elevation of the water table beneath the peak of the hills as influenced by the recharge rates through the spoil.

	Water Table Elevations for Cases Initial	 H-3a	 H-3b	Change
Slope = 5%:	97.5 m	105.3[2] m	117.7 m	12.4[2] m
Slope = 10%:	97.5 m	100.8 m	111.8 m	11.0 m
Slope = 20%:	97.5 m	98.9 m	103.5 m	4.6 m
Recharge Rate:		0.005 m/a	0.050 m/a	
Hydraulic Conductivity:		1×10^{-5} cm/s	1×10^{-5} cm/s	
Storativity:		5×10^{-4}	5×10^{-4}	

[1] Change = (H-3b) - (H-3a)

[2] The water table has reached the ground surface over the entire hill.

Generally the results obtained by varying recharge rates through the spoil are as expected; greater recharge rates lead to a greater elevation of the water table at steady state. It should be noted that, in this group of simulations, even a small increase in the recharge rate leads to significant changes in the position of the water table. Also, the time for the water table to achieve equilibrium increases as the recharge rate decreases.

As might now be expected, comparison of the results for different hills within a given case shows that, for a given recharge rate, broadening the base of the hill results in a rise in the steady state position of the water table because the larger quantity of water moving through the system requires an increased gradient to remove the water. The combination of a higher recharge rate and a large low-angled hill (5% slope of case H-2a) produces a water table that intersects the ground surface.

4.4 LOCAL DISCHARGE AREAS

The simulations presented in this section comprise scenario H-4, a study designed to illustrate the role of discharge features in controlling the configuration of the water table. Depending upon the method of reclamation, the discharge areas could exist as drained or undrained (ponds) topographic lows, or specially constructed ditches. The four different types of discharge conditions that are considered in this analysis are depicted in Figure 21 and summarized as follows:

1. Case H-4a: a topographic low 2.5 m deep at the base of the left side of the hill, referred to as the "left discharge area";
2. Case H-4b: a 2.5 m deep topographic low located far to the left of the base of the hill, referred to as the "far left discharge area";
3. Case H-4c: a 2.5 m deep topographic low at both the left and right base of the hill, referred to as "left and right discharge areas";
4. Case H-4d: a 10 m deep trench located immediately at the base of the left slope of the hill, referred to as the "deep discharge area".

Cases H-4a, H-4b and H-4c, involve the hills that are 20 m high with a base varying in width from 215 m (20% slope), to 430 m (10% slope) to 860 m (5% slope). The spoil is assigned a value of hydraulic conductivity of 1×10^{-5} cm/s, a storativity of 5×10^{-4}, and a high rate of recharge of 0.050 m/a. The setting for case H-4d are the hills shown in Figure 16, that are all 215 m wide at the base and vary in height from 2 m (2% slope) to 5 m (5% slope) to 10 m (10% slope) to 20 m (20% slope). The hydrogeological parameters for the spoil in case H-4d are a hydraulic conductivity of

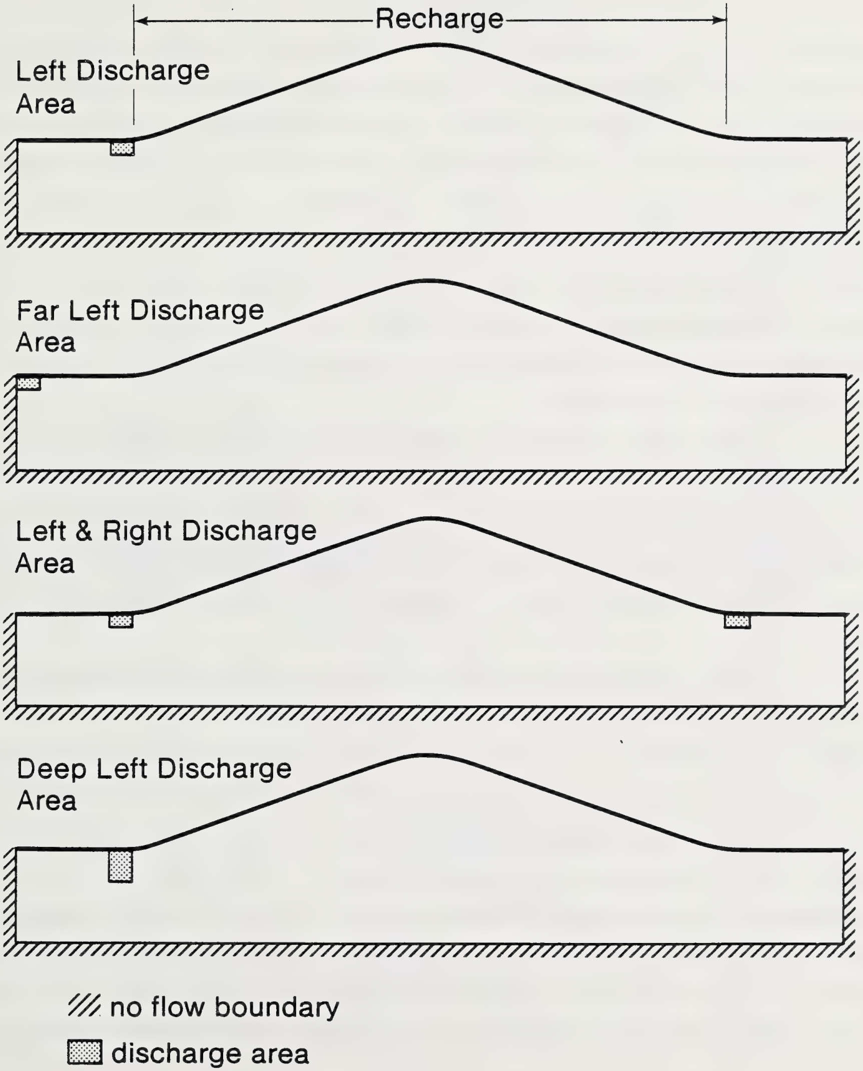


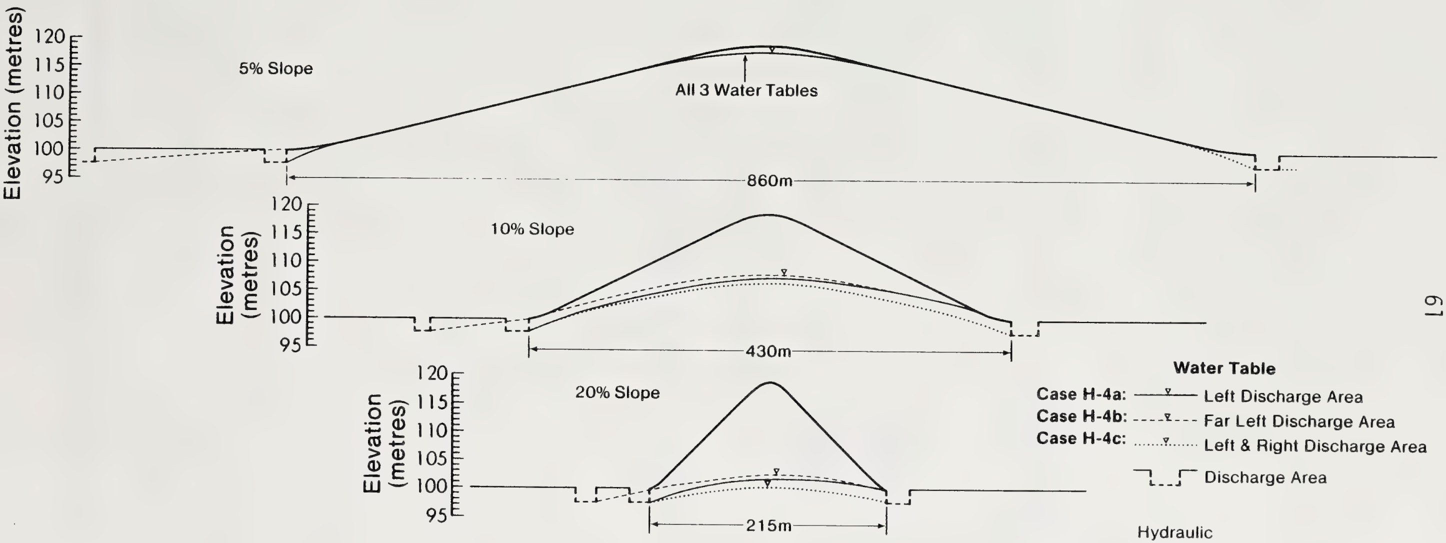
Fig. 21. Schematic illustration of the four surface discharge areas.

1×10^{-6} cm/s, a storativity of 5×10^{-4} and a recharge rate of 0.050 m/a.

The influence of discharge features on the water table configuration within the hills of cases H-4a, H-4b and H-4c is shown by Figure 22. For a given hill, the position of the water table is essentially the same in each case except in the immediate vicinity of the discharge feature. In all these cases, the differences between the highest and the lowest elevation of the water table are less than 2 m (Table 6). The results for a hill with a slope of 10% are typical of these simulations and shows that the water table rises to an elevation of 106.7 m in case H-4c, 107.5 m in case H-4a and 108.2 m in case H-4b, for a range of fluctuation of only 1.5 m. Although the actual distances over which the water table rises within a hill due to changing the location of the discharge zone is small, the greatest relative change occurs within a particular case due to the changing dimensions of the hill. The lowest elevation of the water table occurs in the hill having a 5% slope and the highest elevation occurs in the hill with a slope of 20% (Table 6).

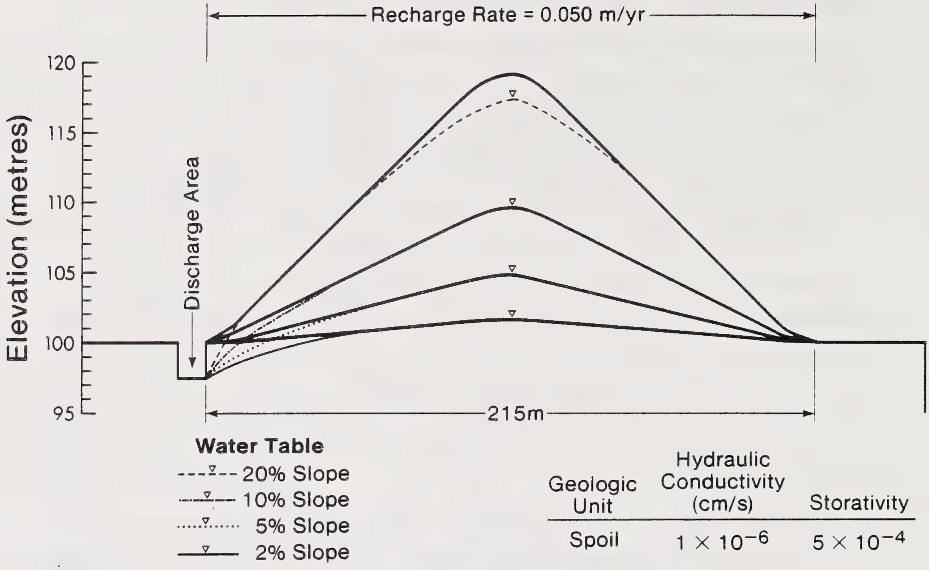
The results obtained for case H-4d (using the hills with dimensions of 215 m wide by 2 m, 5 m, 10 m, or 20 m high) for a left discharge area and for the deep-left discharge area are shown in Figure 23. Again, the actual nature of the surface discharge area does not significantly alter the overall position of the water table. It only changes the length of the seepage face in the immediate vicinity of the ditch.

Thus, for spoil with a low hydraulic conductivity, surface discharge areas exhibit little control over the position of the water table at steady state, or over the length of seepage faces that may develop on the slopes of the hills. Only when these surface discharge features are located immediately at the base of the hill and are quite deep will the water table and the seepage face be lowered, and even at that, only slightly. The effectiveness of the surface drains is controlled by the hydraulic conductivity of the spoil and by the width of the hills. Values of hydraulic conductivity that are relatively low, such as those discussed here, mitigate against the possibility of widely spaced surface drains being used to control the configuration of the water table. As the next series of simulations will show, subsurface drainage is necessary.



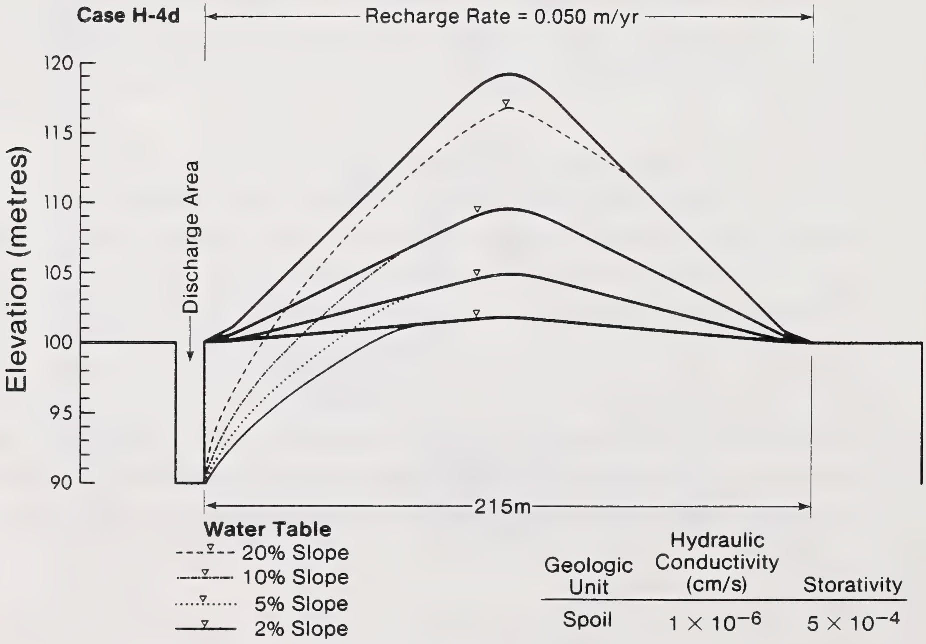
Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-5}	5×10^{-4}

Fig. 22. Position of the water table in hills having a constant height of 20m, as a function of the location of the surface discharge areas.



Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-6}	5×10^{-4}

Case H-4d



Geologic Unit	Hydraulic Conductivity (cm/s)	Storativity
Spoil	1×10^{-6}	5×10^{-4}

Fig. 23. Position of the water table in hills having a constant base width of 215m, depth of the left discharge area varies.

Table 6. Elevation of the water table beneath the peak of the hills as influenced by local surface drainage ditches.

	Water Table Elevations for Cases				Maximum
	Initial	H-4a	H-4b	H-4c	Change[1]
Slope=5%:	97.5 m	117.8[2] m	117.8[2] m	117.8[2] m	-----[2]
Slope=10%:	97.5 m	107.5 m	108.2 m	106.7 m	1.5 m
Slope=20%:	97.5 m	101.5 m	102.4 m	100.4 m	2.0 m
Location of Ditch:		Left	Far Left	Both[3]	
Hydraulic Conductivity (cm/s):		1×10^{-5}	1×10^{-5}	1×10^{-5}	
Storativity:		5×10^{-4}	5×10^{-4}	5×10^{-4}	
Recharge Rate (m/a):		0.050	0.050	0.050	

[1] Maximum Change = (H-4b) - (H-4c)

[2] The water table has reached ground surface over the entire hill.

[3] Drains at both left and right sides at base of the hill

4.5 SUBSURFACE DRAINS

It is apparent from the previous four scenarios that in most natural settings the water table will be present very close to, if not at, the ground surface. The potential for soil salinization is great in these areas. One way to alleviate this potential problem is to use various kinds of drains placed within the spoil beneath a hill to lower water levels. Scenario H-5 investigates two possible types of subsurface drains, a horizontal layer drain comprised of a continuous layer of highly permeable material placed beneath the spoil and discrete open drainage tiles aligned parallel to the length of the hill. These two drain types are illustrated in Figure 24. Both drains are located 10 m below ground surface and are assumed to drain into a surface discharge area at an elevation of 90.0 m. The continuous layer drain is represented by material with a hydraulic conductivity one or two orders of magnitude greater than that of the spoil, and an outflow on its left boundary represented by constant head nodes. The discrete drains are represented as individual constant head nodes and are separated by distances of 50 m, 100 m or 250 m. These simulations involve a hydraulic conductivity of 1×10^{-6} cm/s, a storativity of 5×10^{-4} and a recharge rate of 0.005 m/a applied across the hill. This arrangement of drains is evaluated in relation to four different sizes of hills:

5% slope	5 m height	215 m base
2% slope	5 m height	537 m base
5% slope	10 m height	430 m base
2% slope	10 m height	1075 m base

Two analyses are undertaken with the continuous layer drain. All characteristic of the drain are the same for both cases except the hydraulic conductivity of the drain material, which in case H-5a has a value of 1×10^{-5} cm/s and in case H-5b has a value of 1×10^{-4} cm/s. Results of the simulations are shown in Figure 25 and indicate that its efficiency in mainatining a low water table depends on both its hydraulic conductivity and the size of the hill. As the base of the hill increases, the elevation of the water table increases (Table 7). For example, for case H-5a, the elevation of the water table increases from 99.4 m to 106.3 m to the ground surface, beneath the centre of the hill, as the base of the hill increases in width from 215 m to 430 m to 537 m and 1075 m, respectively (Table 7). The same pattern holds for case H-5b where the water table continuously rises from 96.6 m to 99.1 m to 106.4 m within the hills with bases that are 430 m, 537 m and 1075 m wide (Table 7). In all the simulations depicted in Figures 25, a drain with a hydraulic conductivity of 1×10^{-5}

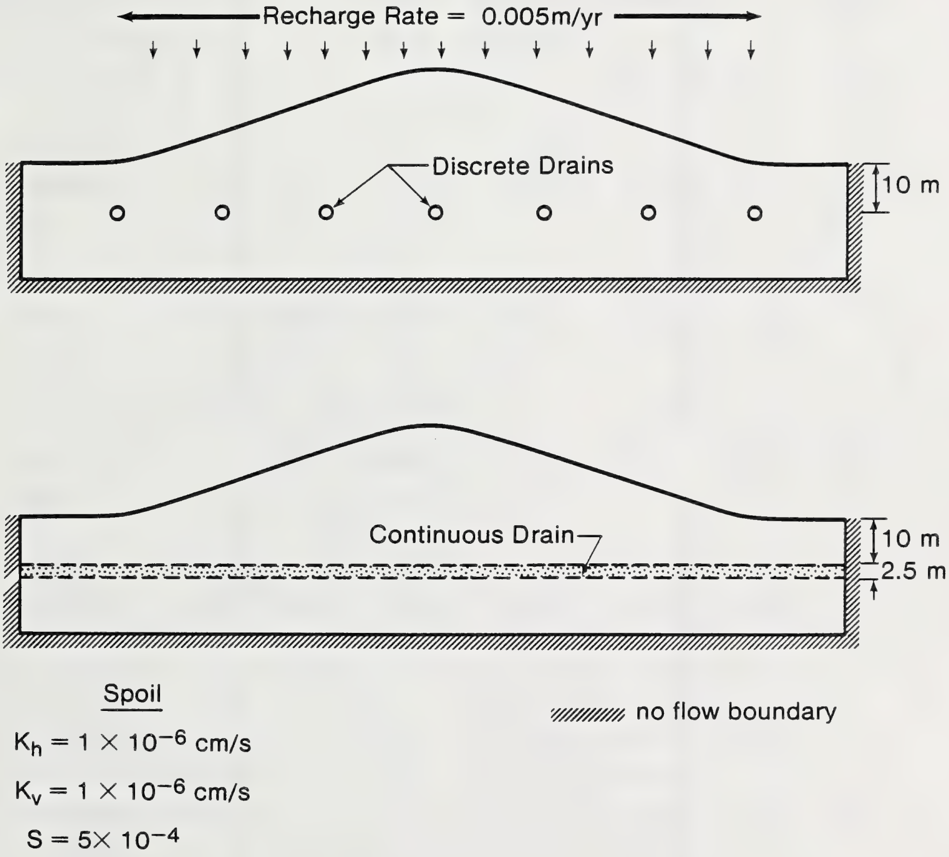


Fig. 24. Schematic illustration of the two subsurface drain configurations.

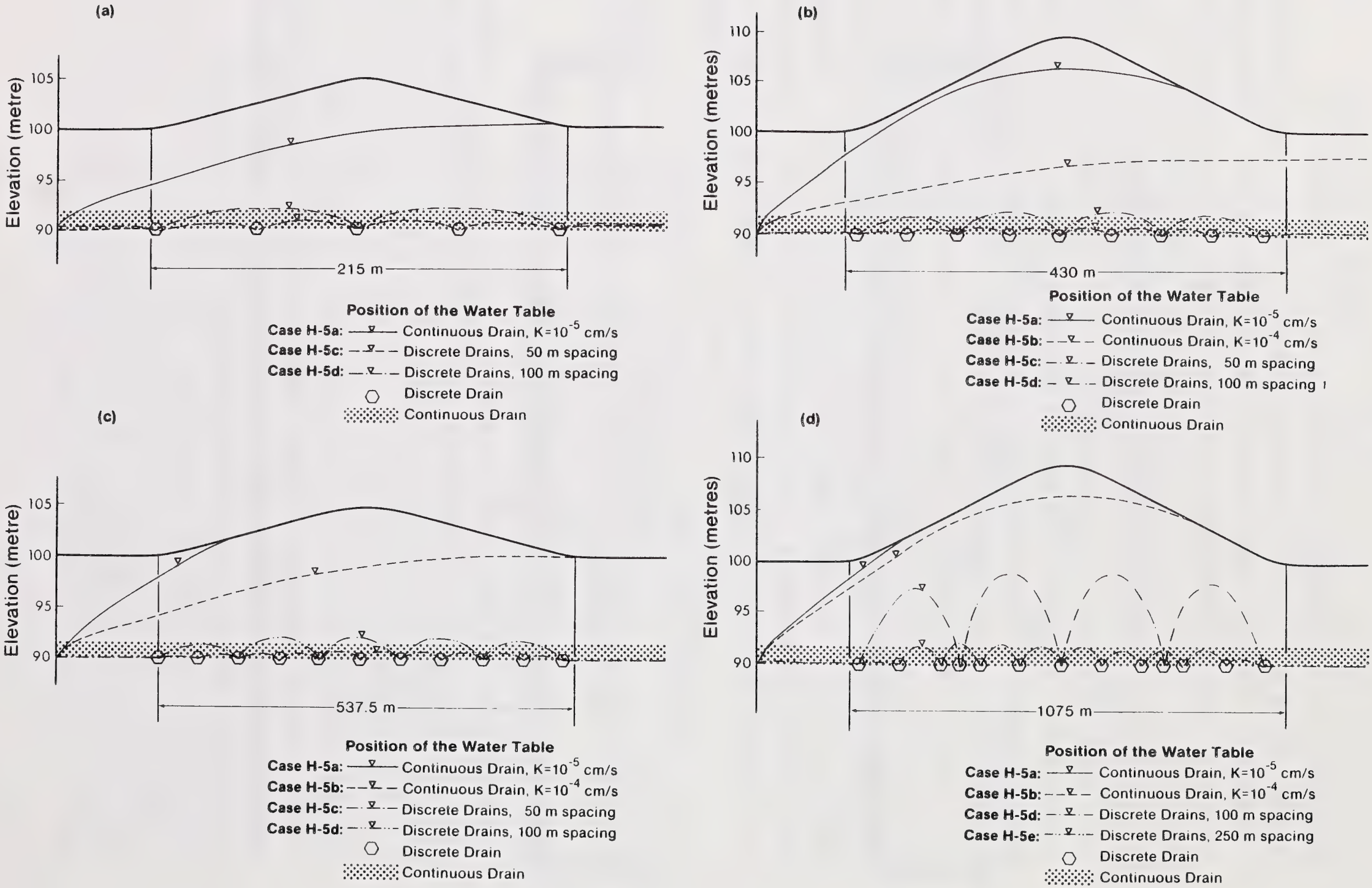


Fig. 25. Position of the water table in hills as a function of subsurface drain type and characteristic.

Table 7. Elevation of the water table beneath the peak of the hills as influenced by continuous and discrete subsurface drains.

	Elevation of the Water Table in m for Cases					
	Initial	H-5a	H-5b	H-5c	H-5d	H-5e
Drain Type:		contin.	contin.	discrete	discrete	discrete
K of Drain (cm/s):		1×10^{-5}	1×10^{-4}	-----	-----	-----
Drain Spacing:		-----	-----	50 m	100 m	250 m
Hill 5 m x 215 m						
Centre[1]:	90.0	99.4	-----	90.8	92.1	-----
Right[2]:	90.0	100.0[3]	-----			
Hill 5 m x 537 m						
Centre[1]:	90.0	104.6[3]	99.1	90.7	92.2	-----
Right[2]:	90.0	100.0[3]	97.4			
Hill 10 m x 430 m						
Centre[1]:	90.0	106.7	96.6	90.7	92.0	-----
Right[2]:	90.0	100.0[3]	100.0[3]			
Hill 10 m x 1075 m						
Centre[1]:	90.0	109.5[3]	106.4	-----	92.0	99.0
Right[2]:	90.0	100.0[3]	100.0[3]			
K of Spoil (cm/s):		1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}
Storativity of Spoil:		5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
Recharge Rate (m/a):		0.005	0.005	0.005	0.005	0.005

[1] Beneath the centre of the hill for a continuous drain or maximum elevation between individual discrete drains.

[2] Base of the slope on the right side of the hill.

[3] The water table has reached ground surface.

cm/s is not sufficiently permeable to keep the water table from intersecting the ground surface to the right of the hill. Also, for case H-5a, as the height of the hill decreases, the water table intersects the ground surface sooner than it would within a higher hill.

By increasing the hydraulic conductivity of the drain simulated by case H-5b, by one order of magnitude to 1×10^{-4} cm/s, the water table is lowered significantly in the smaller hills (Figure 25). In fact, beneath both the 215 m and the 430 m wide hills, the water table is no longer in contact with the ground surface to the right of the hill. However, although the drain simulated by case H-5b did lower the water table within the hill with a width of 1075 m (Figure 25), a hydraulic conductivity of 1×10^{-4} cm/s is still not large enough to prevent the water table from reaching the ground surface along a significant portion of the hill to the right of its crest. If the hydraulic conductivity of the drain material is increased further, the elevation of the water table within the spoil should decline to acceptable levels.

Discrete open drains placed parallel to the length of the hill produce a much greater lowering effect on the elevation of the water table than the continuous drains (Figure 25). This reflects the much more effecient drainage provided by open drains, which effectively have a hydraulic conductivity much larger than the continuous drain. In the three cases simulated with this type of drain, cases H-5c, H-5d and H-5e, the resulting water table is only a few metres above the drain (Table 7). The major observation resulting from these simulations is that the lowering of the water table is essentially independent of the size of the hill, but depends primarily on the spacing of the drain. The maximum elevation of the water table under the influence of a drain with a 50 m spacing is approximately 90.7 m (0.7 m above the drain) and a drain with a 100 m spacing causes the water table to rise to an elevation of approximately 92.0 m (2.0 m above the drain). Although only one simulation was run with a drain spacing of 250 m (Figure 25), it is expected that the elevation of the water table of other hills would also be approximately 99.0 m (9.0 m above the drain).

This set of analyses demonstrates the importance of proper drain design in maintaining the water table at a sufficient depth below the surface of the spoil. If the hill is not very wide, less than approximately 500 m, a hydraulic conductivity contrast between the continuous drain and the spoil of one order of magnitude would be sufficient to maintain an acceptable water level. As the hill width increases, a higher hydraulic conductivity contrast is needed. But, for large hills, in the order of 1000 m or more wide, this type of drain is not adequate to lower the water table to a suitable depth below the surface of the spoil. Lowering the water table with discrete drains maintains the lowest water level and although the position of the water table increases as the individual drain spacing increases, it will still be only a few metres above the elevation at which the drains are placed.

5. DISCUSSION

This work has shown that mathematical models can provide an important tool for studying various groundwater problems related to the strip mining of coal. Modelling at the regional scale yields the following set of conclusions.

1. Strip mining has the potential to influence groundwater conditions on a regional as well as a local scale. Dewatering during the development of the mine has the predictable effect of lowering water levels over an increasingly larger area around the mine. During the relatively short period of mining, the flow system does not have an opportunity to reach steady state. However, once the mining has been completed and dewatering ceases, the response of water levels can become complex depending upon features of the hydrogeological setting. Early in the post-mining period, it is possible for water levels to continue to decline in the vicinity of a mine, while rising within the mine spoil. During this time, groundwater actually continues to flow to the low in hydraulic potential created by dewatering. This situation is promoted by relatively low recharge rates and a geological system with a low permeability. With higher recharge rates and more permeable geologic units, this behaviour tends to disappear. Ultimately, the flow system returns to a post-mining, steady state configuration.
2. Hydrogeological features in the vicinity of the mine, such as areas of discharge or sources for induced infiltration, can in some cases attenuate the impact of mining on water levels. A discharge area forming upgradient from the mine in a relatively high hydraulic conductivity system significantly reduced the magnitude of the permanent rise in water levels that might have otherwise occurred. A simulation with a surface water source upgradient from the site showed how induced infiltration can be effective in controlling the spread in the zone of declining water levels during mining. Once the water levels are able to rise sufficiently high in the post-mining period, the pond operates as a local discharge area that is able to control the long-term rise in water levels.
3. At least three factors related to mining can produce significant changes in the post-mining steady state configuration of water levels

relative to the pre-mining system. The first is the character of the landscape following mining and reclamation. In a case where the geological system is relatively permeable, maintaining a drained depression in the spoil produces a permanent water level decline (relative to the pre-mining situation) around the depression. The zone of influence of this depression will diminish as the hydraulic conductivity of the spoil or flow system decreases.

The other two factors are the recharge rate through the spoil and the hydraulic conductivity of the spoil. Permanently higher water levels will develop if it is possible for more recharge to enter the system through spoil, or if the gross permeability of the system decreases. Such changes to the permeability could develop directly when permeable geological units are replaced by less permeable spoil, or indirectly when the hydraulic continuity of thin, very permeable units is disrupted. Permanently lower water levels will develop when recharge through spoil is decreased or the gross permeability of the system is increased.

4. The timing of post-mining responses in water levels depends upon features of the hydrogeological setting. The time required for the system to reach a new steady state following mining increases markedly as the gross hydraulic conductivity and recharge rates for the system decrease. The storativity of the mine spoil also influences the timing of water level changes. With a relatively high storativity, water levels change much more slowly than when the value of storativity is relatively low. More importantly, from a regulatory viewpoint, the time required for all of these systems to return to equilibrium can be significant.

At the mine-scale, the way the spoil resaturates depends in a complex way on the magnitude and distribution of recharge, and the hydraulic conductivity of spoil and geological units. The most important conclusions from simulations at this scale can be summarized as follows.

1. During the early history of spoil resaturation, high gradients along the water table can develop as a consequence of one or more of the following conditions: spatially distributed recharge especially from ponds, a lack of bottom drainage from units below the mine, and

spoil with a low hydraulic conductivity. Conversely when conditions opposite to these develop, the gradients along the water table are relatively low.

2. When water levels in the spoil generally rise above those in units surrounding the mine, those conditions listed above operate to determine whether the water table ultimately rises to the ground surface across the spoil (high gradients) or at a relatively limited number of topographically low positions. In addition, recharge that might have originally been uniformly distributed during the earlier stages of resaturation can become spatially variable once the water table begins to interact with the ground surface.
3. The rate at which the water table recovers in the spoil is proportional to the magnitude of the recharge rates and lateral inflows from geological units adjacent to the mine. Although our work has yet to examine the particular role of storativity, it is clear from the regional simulations that this parameter will be of importance as well.

Moving to the results of the simulations of spoil hills, it is apparent that the same hydrogeologic parameters, recharge rates and hydraulic conductivity distributions control the steady state hydraulic head. In addition, these simulation trials demonstrate the effectiveness of various reclamation strategies in controlling water levels. The most important conclusions are summarized as follows.

1. Hydraulic conductivity is an important parameter controlling the elevation of the water table within a spoil hill. If hydraulic conductivity is varied by as little as only one order of magnitude, significant changes in the position of the water table may occur. As values of hydraulic conductivity are decreased while recharge rates remain constant, the water table may intersect the ground surface over much of the hill.
2. The dimensions of the hill (height, width, slope) may significantly influence the position of the water table within a spoil hill. The results of this study indicate that as the width of the hill increases, the water table rises, and in some cases reaches the ground surface. This result is caused by increased volumes of water entering the hill along longer slopes, and by longer flow paths to the discharge areas. The height of the hill exhibits less control. As the height of a

hill increases, and the slope increases, the potential for the water table to reach the ground surface diminishes.

3. The elevation of the water table is relatively sensitive to the rate of recharge. Small variations in the recharge rates may produce large changes in the position of the water table and significant areas of waterlogging along the lower slope of the hills.
4. For the cases we have examined, the presence of local surface discharge areas have a negligible influence on the overall position of the water table. The water table is only affected in the immediate vicinity of the discharge area.
5. Subsurface drains can have an important influence on the elevation of a water table beneath the reclaimed areas. Generally, the effect of a drain configuration is independent of the hill size. Discrete drains, which rapidly drain water through open tiles, will keep the water table at elevations within a few metres of the drain. Continuous drains, comprised of a permeable material, remove water at a much slower rate when the hydraulic conductivity of the drain is only slightly greater than the spoil. This kind of drain appears to be adequate only beneath small hills.

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